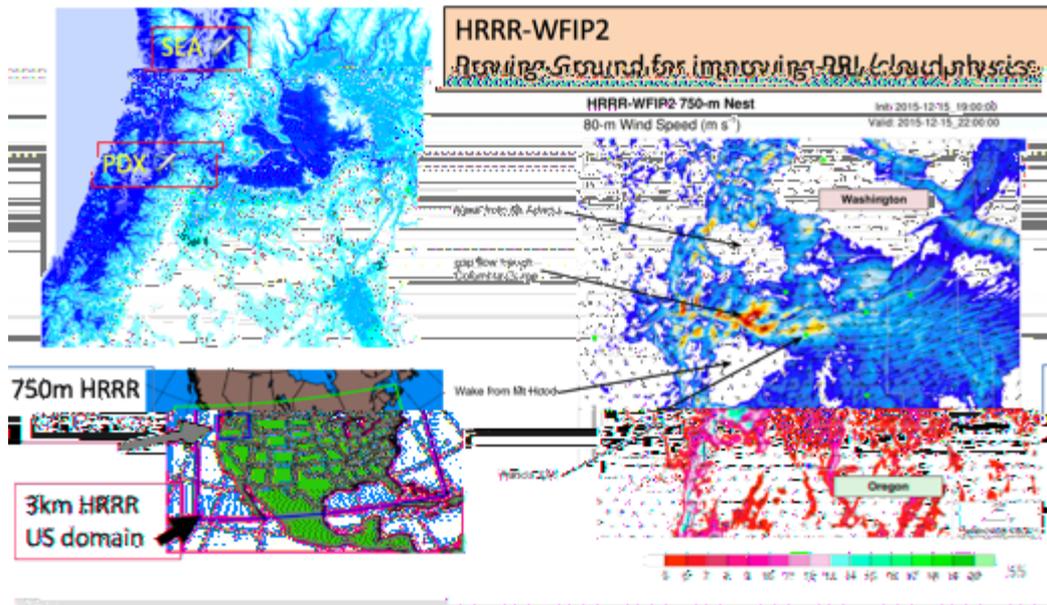


# How numerical weather prediction models work - Applications for power system operations.

Stan Benjamin

NOAA /Earth System Research Lab  
Boulder, Colorado

Joseph Olson, Jaymes Kenyon,  
Terra Ladwig, Eric James  
Curtis Alexander, Stephen Weygandt,  
Ming Hu, Tanya Smirnova



# Weather models / HRRR / RE application

- **How do weather models work?**
- What are the unique designs of the HRRR and RAP weather models?
- What is needed for improved models for turbine-level winds and downward solar radiation?

# Prediction of High-Impact Weather

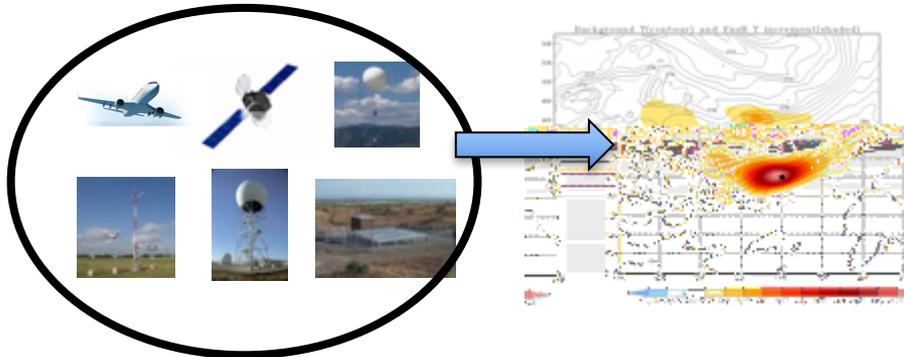
High-performance Computing



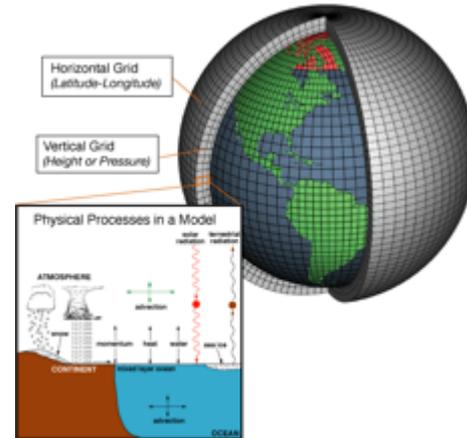
High-density, High-frequency Observations



Advanced Use (Assimilation) Of Observations

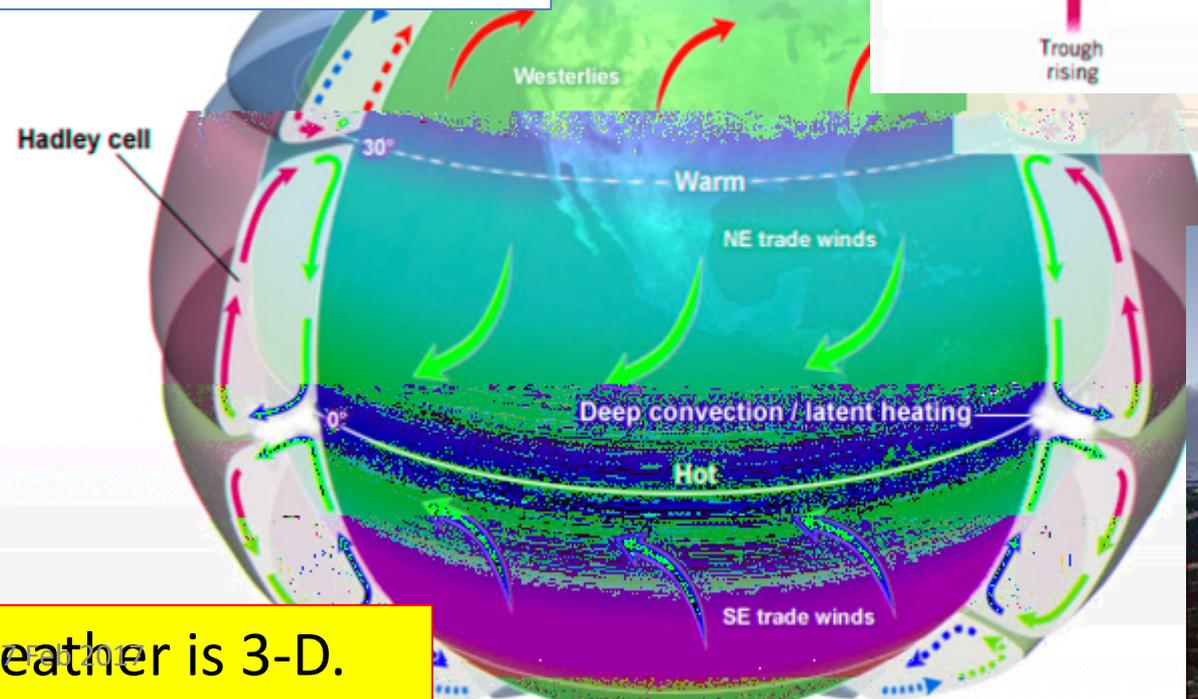
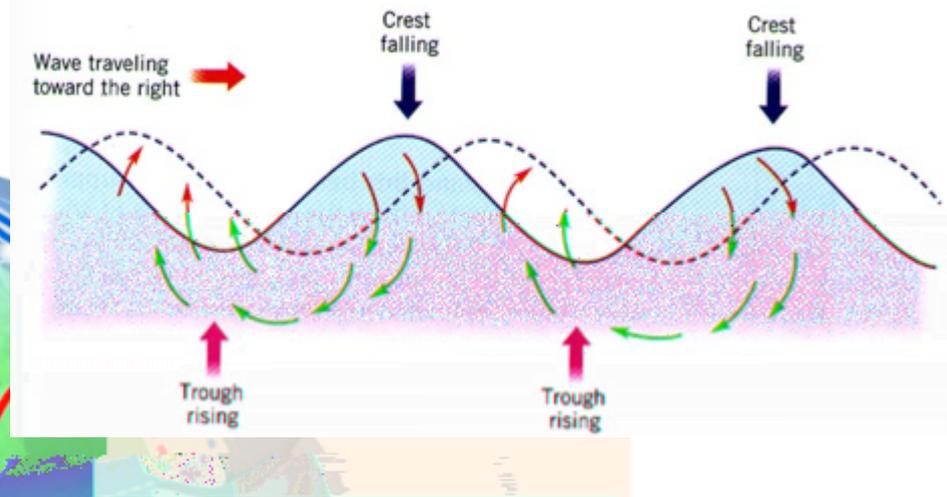
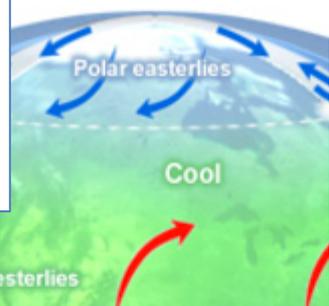


Advanced Numerical Weather Model

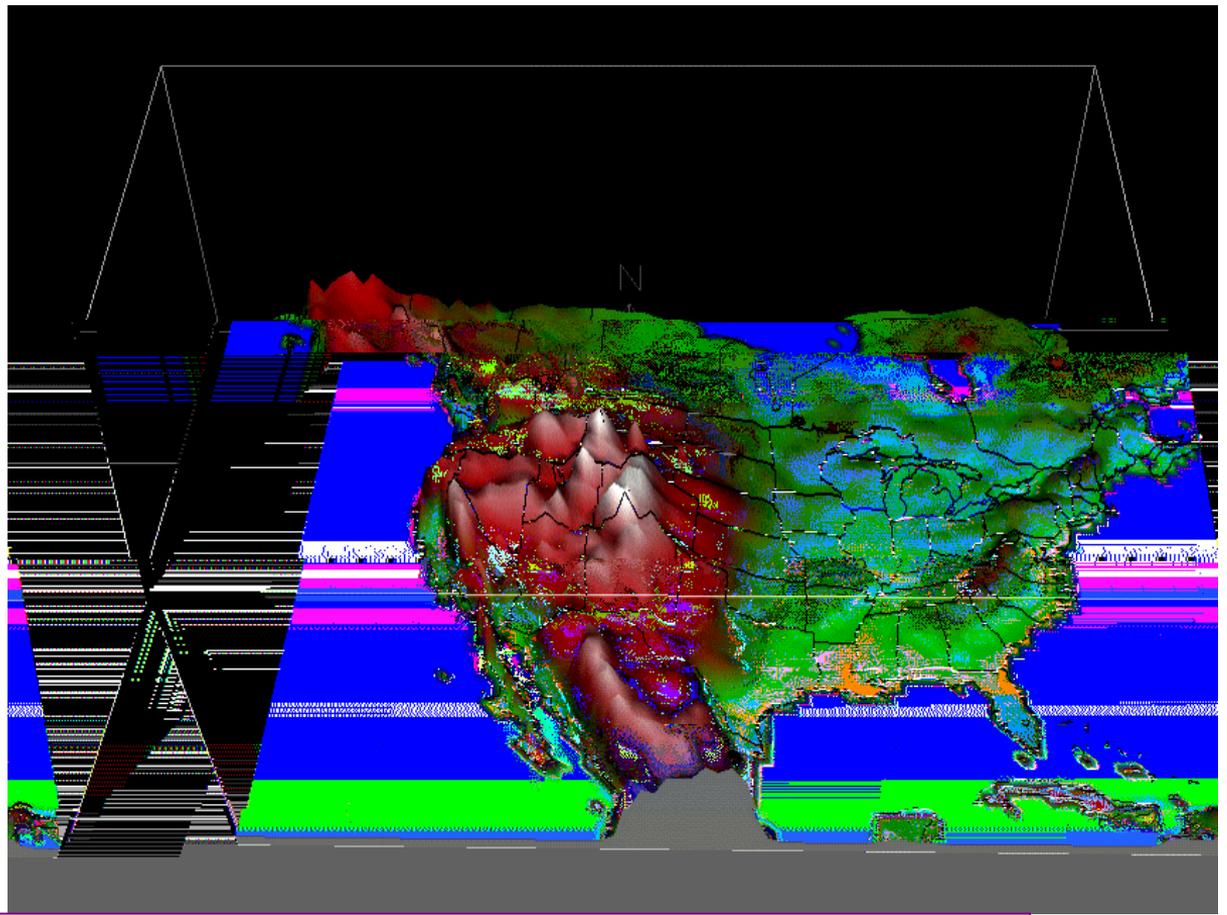


# Earth's atmosphere driven by

- uneven heating
- rotation

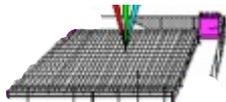


Weather is 3-D.

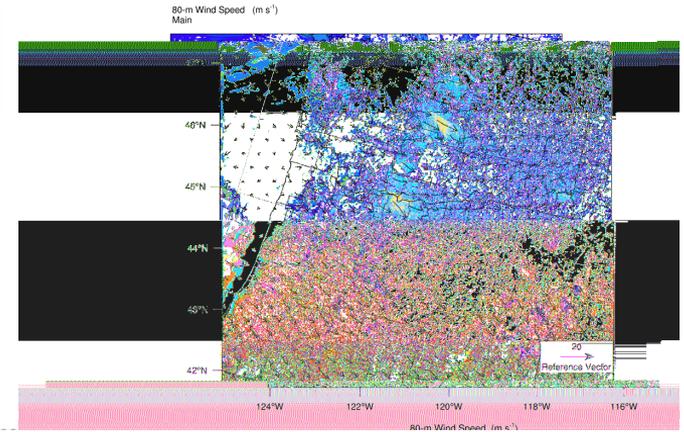
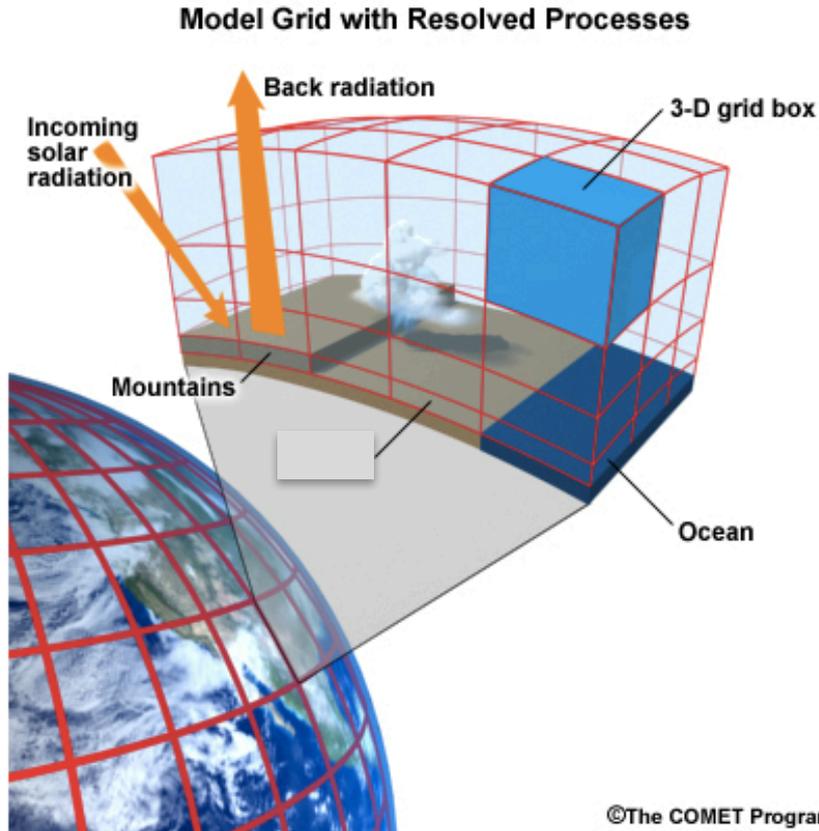




# Operational Prediction Process



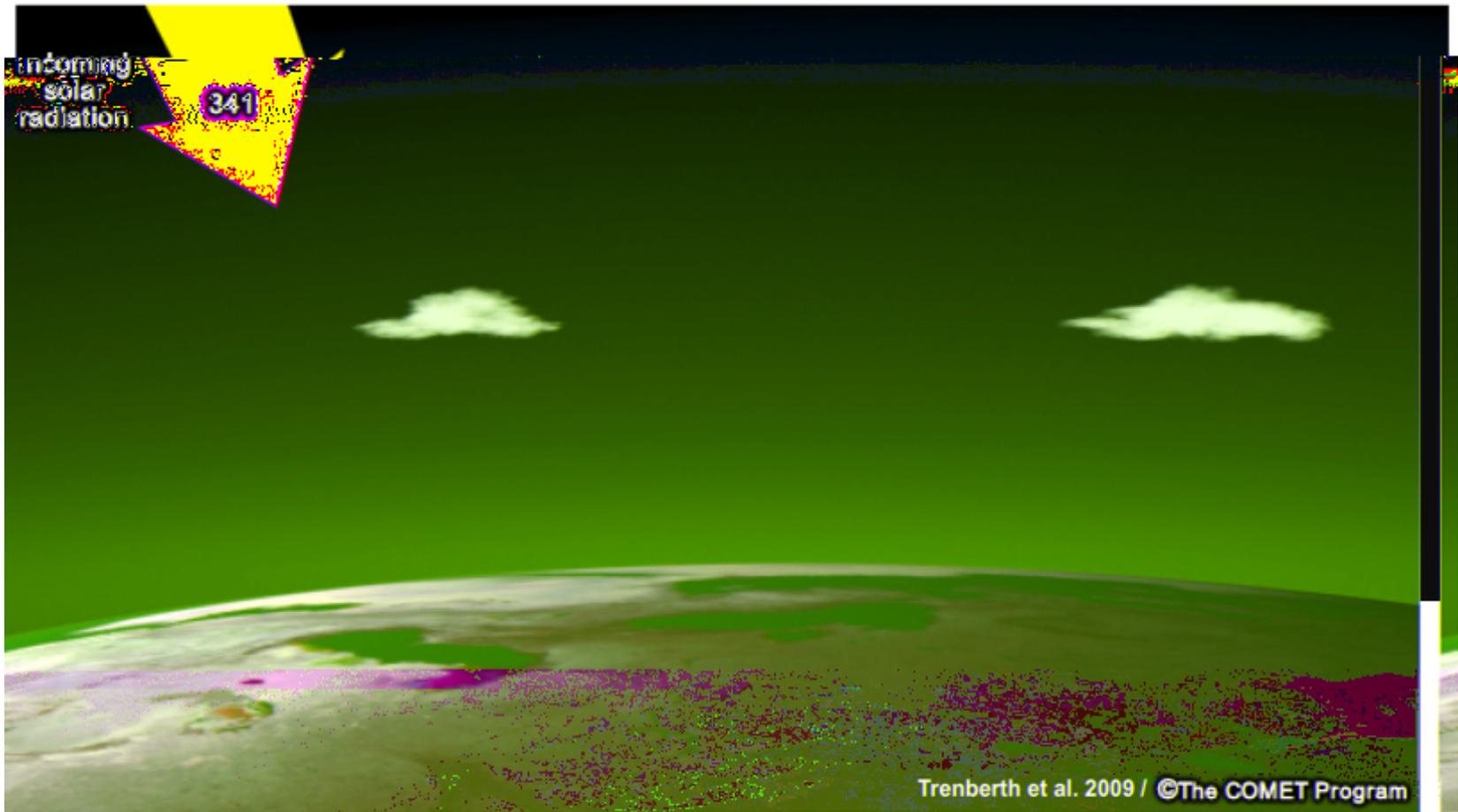
# What is a weather model?



## Forecast

- temperature
- wind (E-W and N-S)
- water vapor
- cloud / hydrometeors (cloud water, ice, rain, snow, hail)

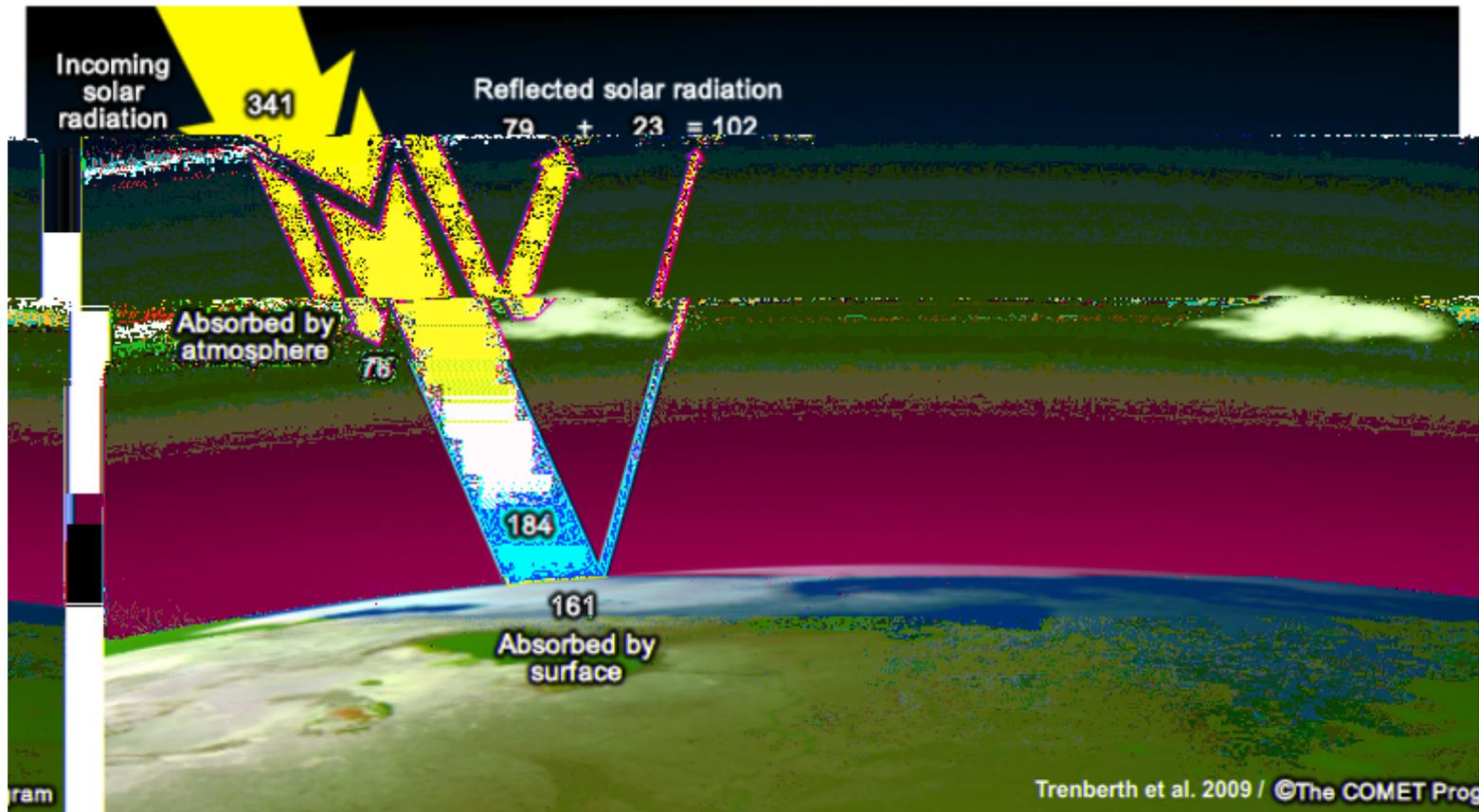
Parameterizations for radiation, mixing, cloud processes, land-surface, chemistry, ocean, ...



**Solar energy drives the Earth's climate system. Flow of energy based on measurements**

7 Feb 2017

**Numbers are best estimates ( $\text{W}/\text{m}^2$ , 2009)**



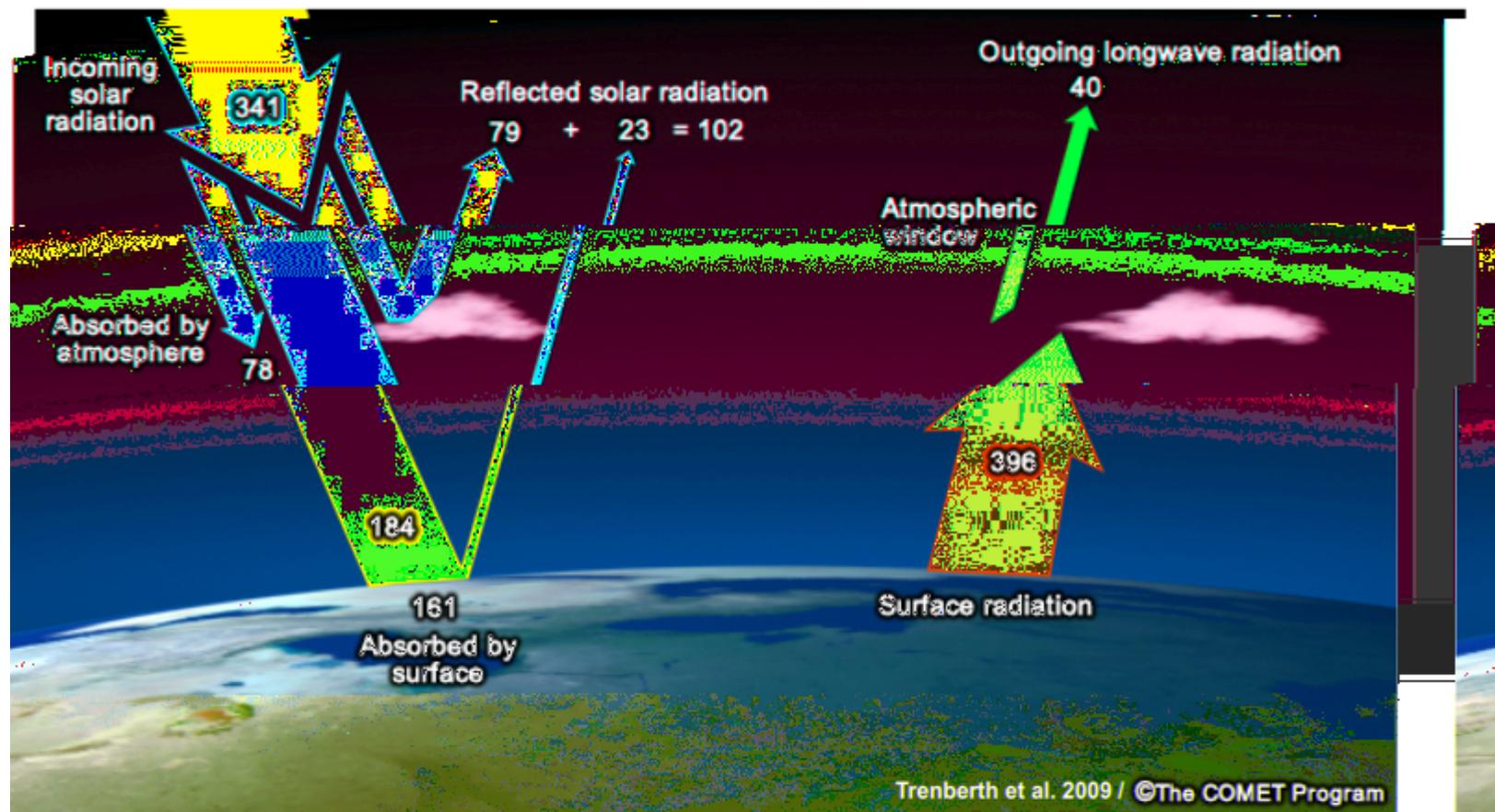
ly

Rest makes its way to the surface

- Most is absorbed
- Some is also reflected

Difference between incoming and reflected energy

- Total available to climate system
- Two-thirds absorbed by the surface

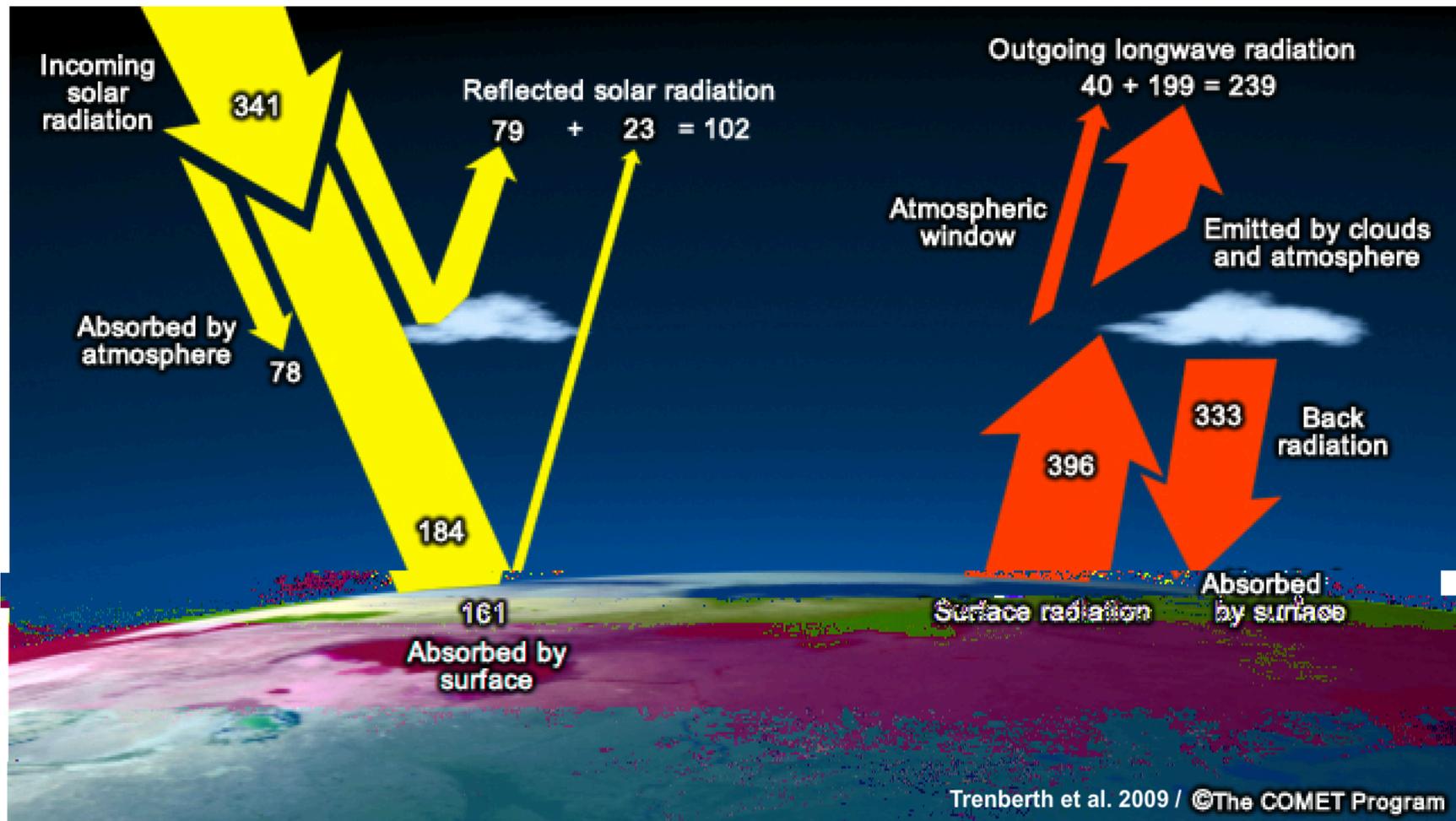


Some radiation to space through atmospheric window

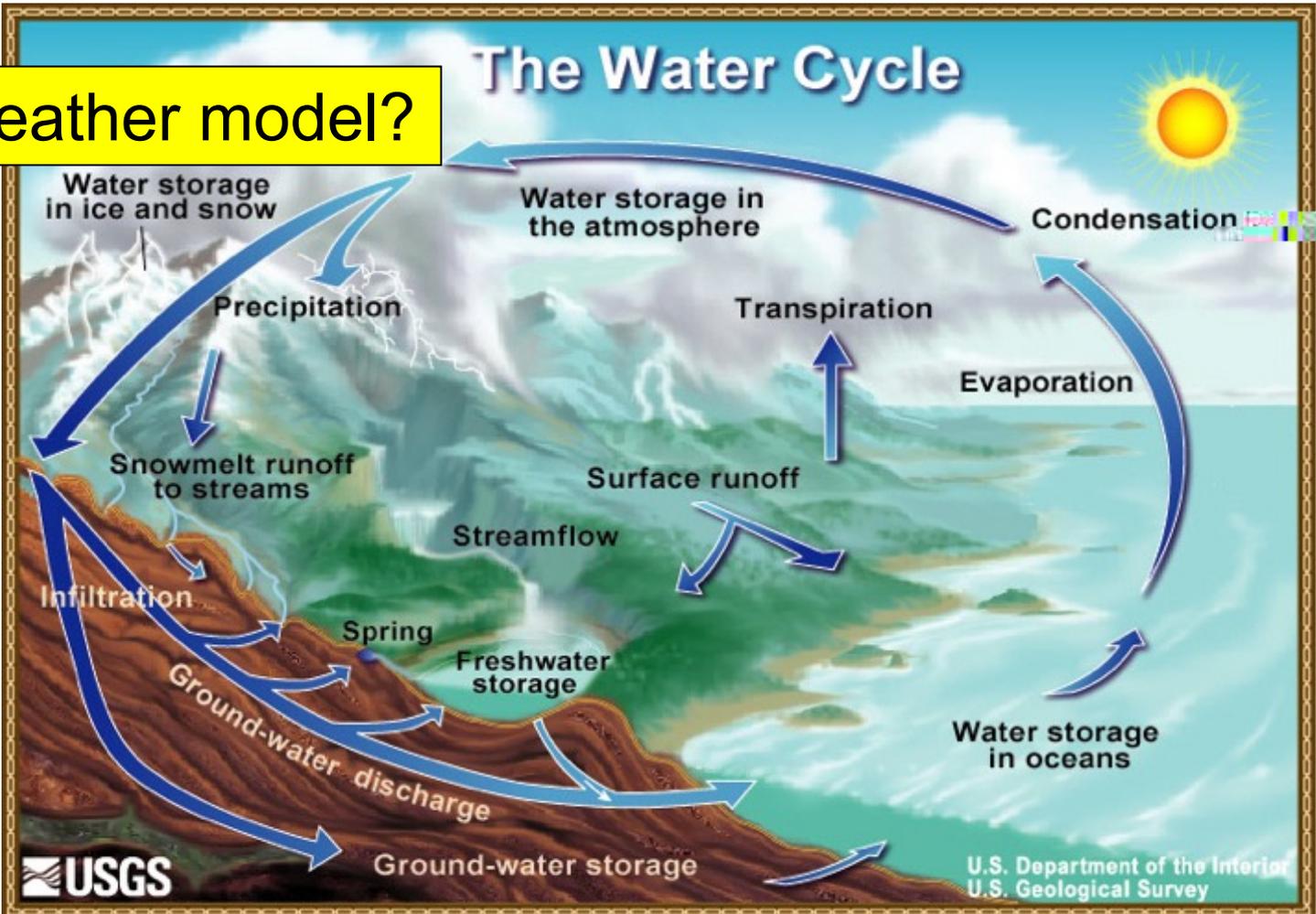
Greenhouse gases absorb longwave radiation and radiate it

some absorbed by clouds

- Some radiated upward toward space

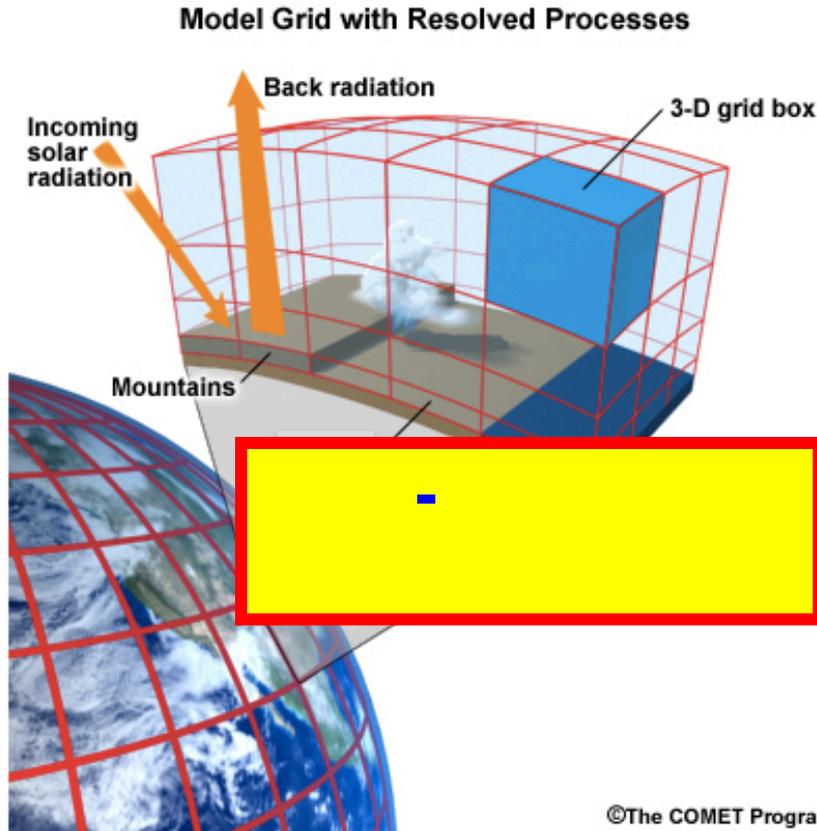


What is a weather model?



# What is a weather model?

$$\frac{\partial X}{\partial t} = \dots$$



To directly simulate processes in Earth's

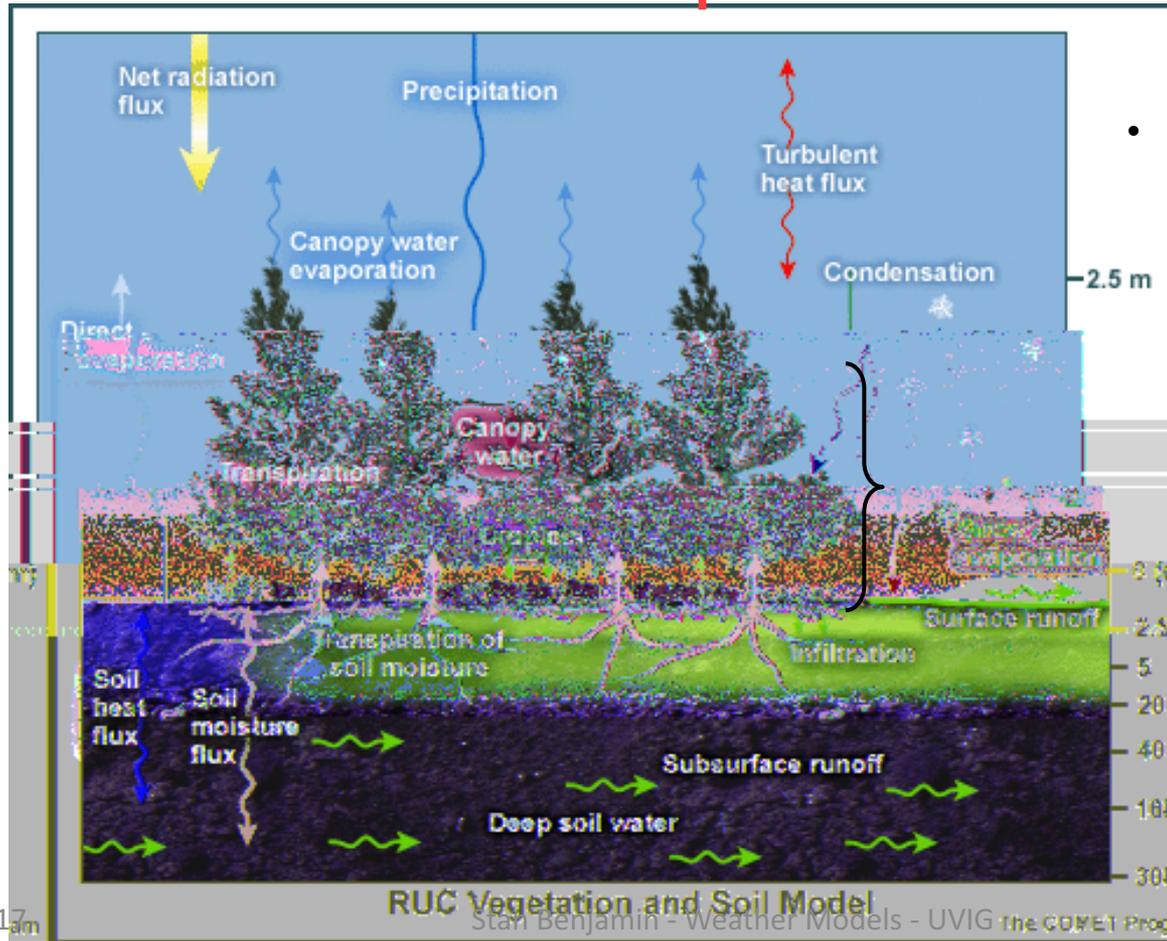
- Set of equations using fundamental laws of physics

Equations of motion or primitive equations

- Used by both climate and weather prediction models
- Balance forces acting in three dimensions
- Conserve mass
- Track the temperature of each grid box
- Track the amount of moisture and other trace products

Parameterizations for radiation, mixing, cloud processes, land-surface, chemistry, ocean, ...

# 1-d land-surface parameterization

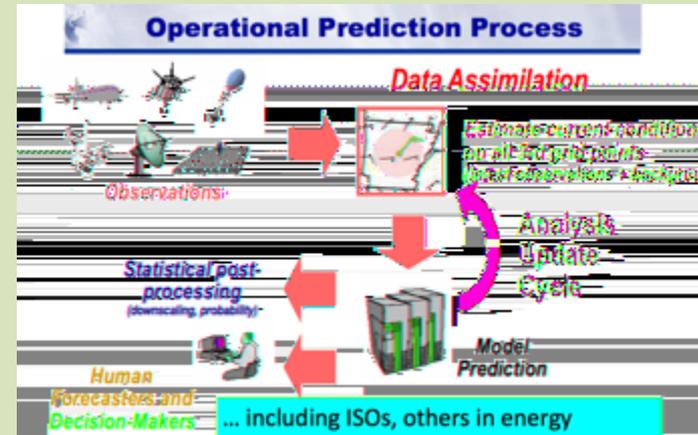


- Multi-level forecasts of soil moisture, soil temperature, snow cover, snow depth, multi-level snow temperature

Weather is 3-D and is even strongly affected by surface.

# Weather models / HRRR / RE application

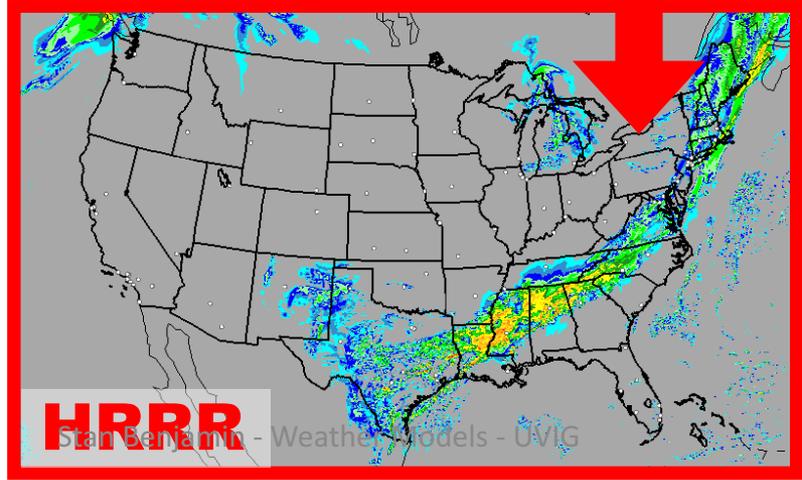
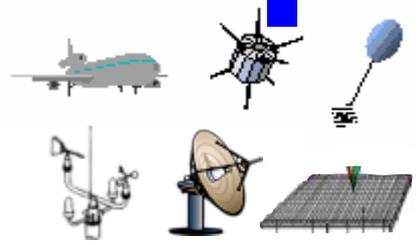
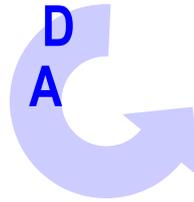
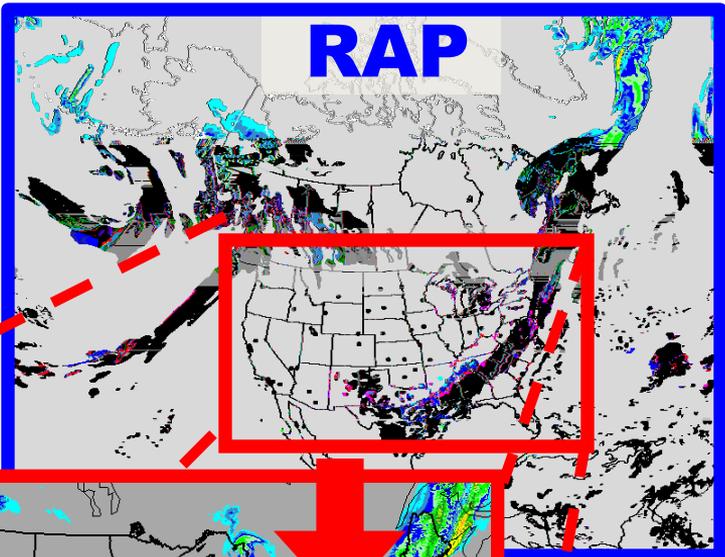
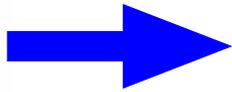
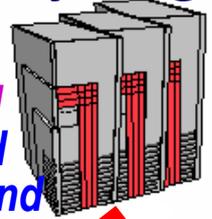
- How do weather models work?
- **What are the unique designs of the HRRR and RAP weather models?**
- What is needed for improved models for turbine-level winds and downward solar radiation?



# 13km Rapid Refresh and 3km HRRR

**Hourly cycling model**

**Advanced Radar and Cloud, Wind**





# RAP/HRRR: Hourly-Updating Weather Forecast Suite

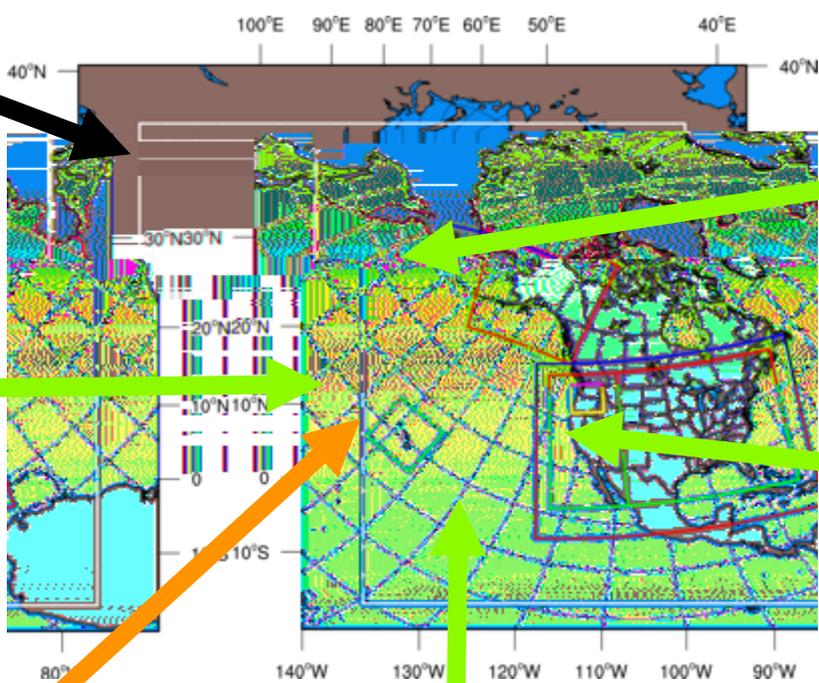
( )

Initial & Lateral  
Boundary Conditions

( )

&

( )



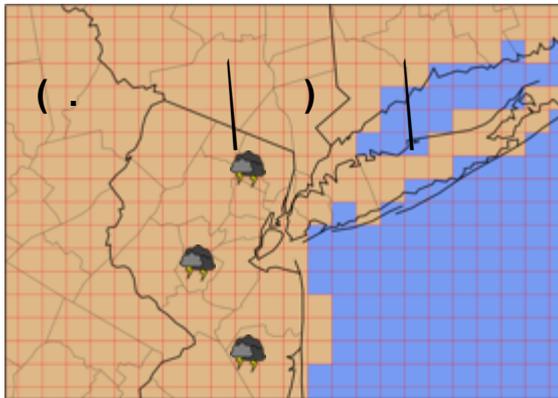
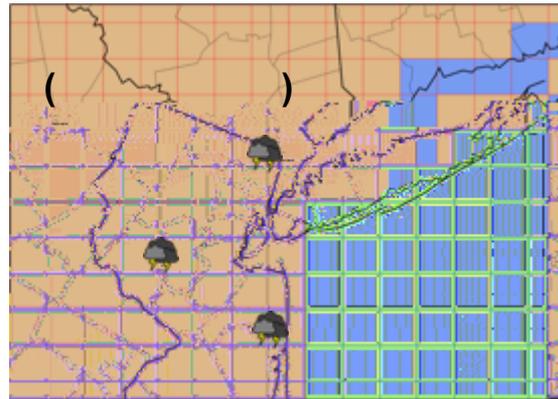
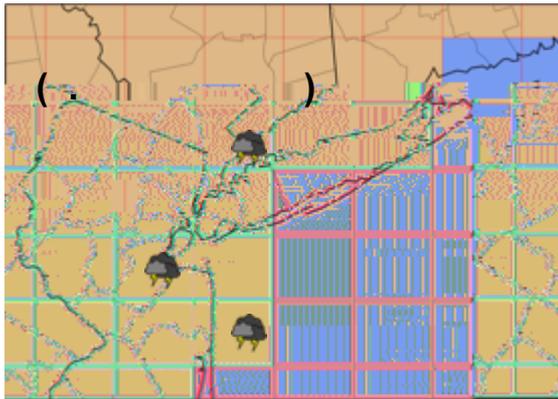
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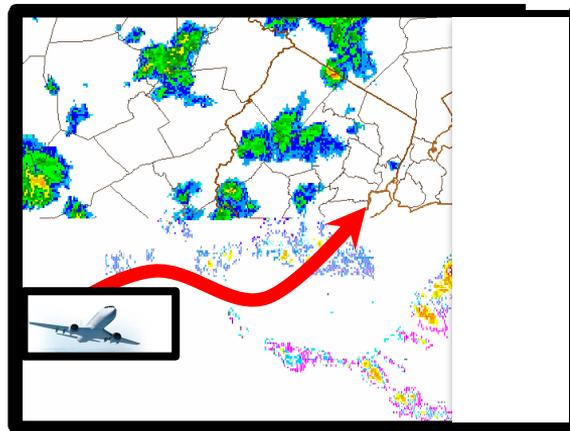
# High-Impact Prediction Needs: Higher Resolution Models





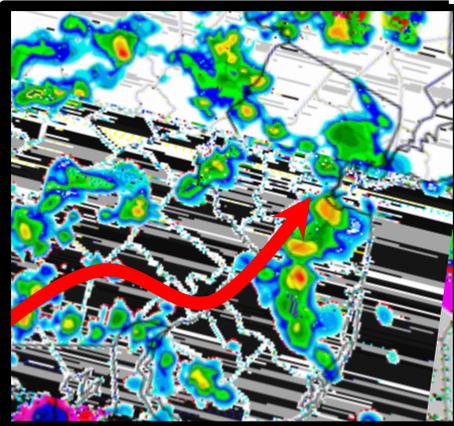
# High-Impact Prediction Needs: Advanced NWP Model

07 June 2012 5 PM EDT  
Reality



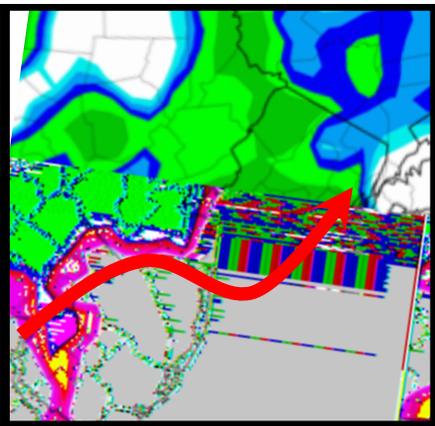
Aircraft must  
Navigate Around  
Thunderstorms

3-km HRRR  
Explicit  
Convection 6 hr forecast

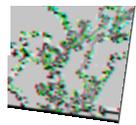
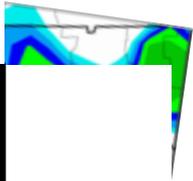


Accurate Storm  
Structure  
  
Accurate Estimate of  
Permeability

13-km RAP  
Parameterized  
Convection 6 hr forecast



No Storm Structure  
  
No Estimate  
of Permeability





# HRRR Users and Applications





# RAPv3/HRRRv2 Changes to Observations Assimilated

**New in RAPv3/HRRRv2 at NCEP**

**Radial velocity (RAPv3)**

**Lightning (RAPv3)**

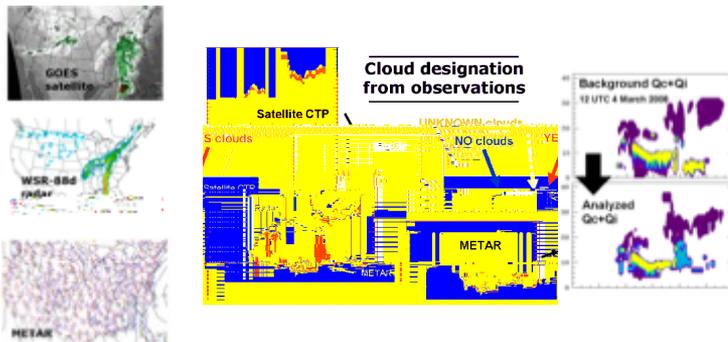
**Mesonet (RAPv3/HRRRv2)**

**RARS radiances (RAPv3)**

| Hourly Observation Type       | Variables Observed   | Observation Count |
|-------------------------------|--|-------------------|
| Rawinsonde                    | Temperature, Humidity, Wind, Pressure                              | 120               |
| Profiler – 915 MHz            | Wind, Virtual Temperature  | 20-30             |
| Radar – VAD                   | Wind   | 125               |
| <b>Radar</b>                  | <b>Radial Velocity</b>   | <b>125 radars</b> |
| Radar reflectivity – CONUS    | 3-d refl → Rain, Snow, Graupel                                     | 1,500,000         |
| <b>Lightning</b>              | <b>(proxy reflectivity)</b>  | <b>NLDN</b>       |
| Aircraft                      | Wind, Temperature  | 2,000 -15,000     |
| Aircraft - WVSS               | Humidity   | 0 - 800           |
| Surface/METAR                 | Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather | 2200 - 2500       |
| <b>Surface/Mesonet</b>        | <b>Temperature, Moisture, Wind</b>                                 | <b>~5K-12K</b>    |
| Buoys/ships                   | Wind, Pressure   | 200 - 400         |
| GOES AMVs                     | Wind   | 2000 - 4000       |
| AMSU/HIRS/MHS ( <b>RARS</b> ) | Radiances  | 1K-10K            |
| <b>GOES</b>                   | <b>Radiances</b>   | <b>large</b>      |
| GOES cloud-top press/temp     | Cloud Top Height   | 100,000           |
| GPS – Precipitable water      | Humidity   | 260               |
| WindSat Scatterometer         | Winds  | 2,000 – 10,000    |

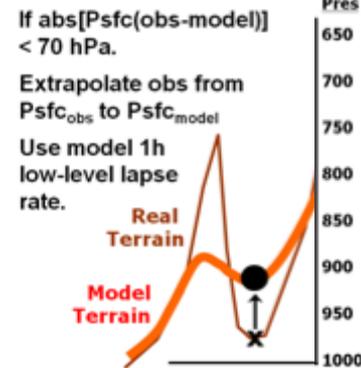
# Rapid Refresh/HRRR Specific Analysis Features

## Cloud and hydrometeor analysis

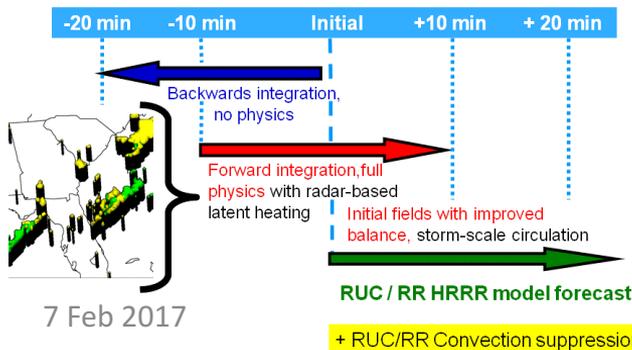


## Special treatments for surface observations

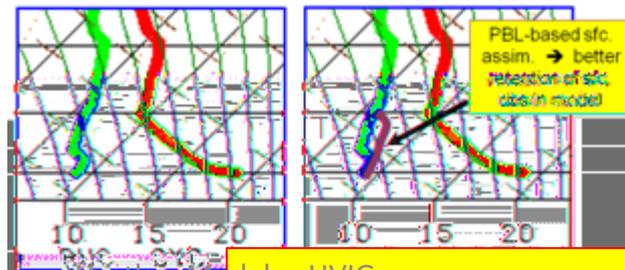
### Elevation correction



## Radar/lightning assimilation



### PBL-based pseudo-observations

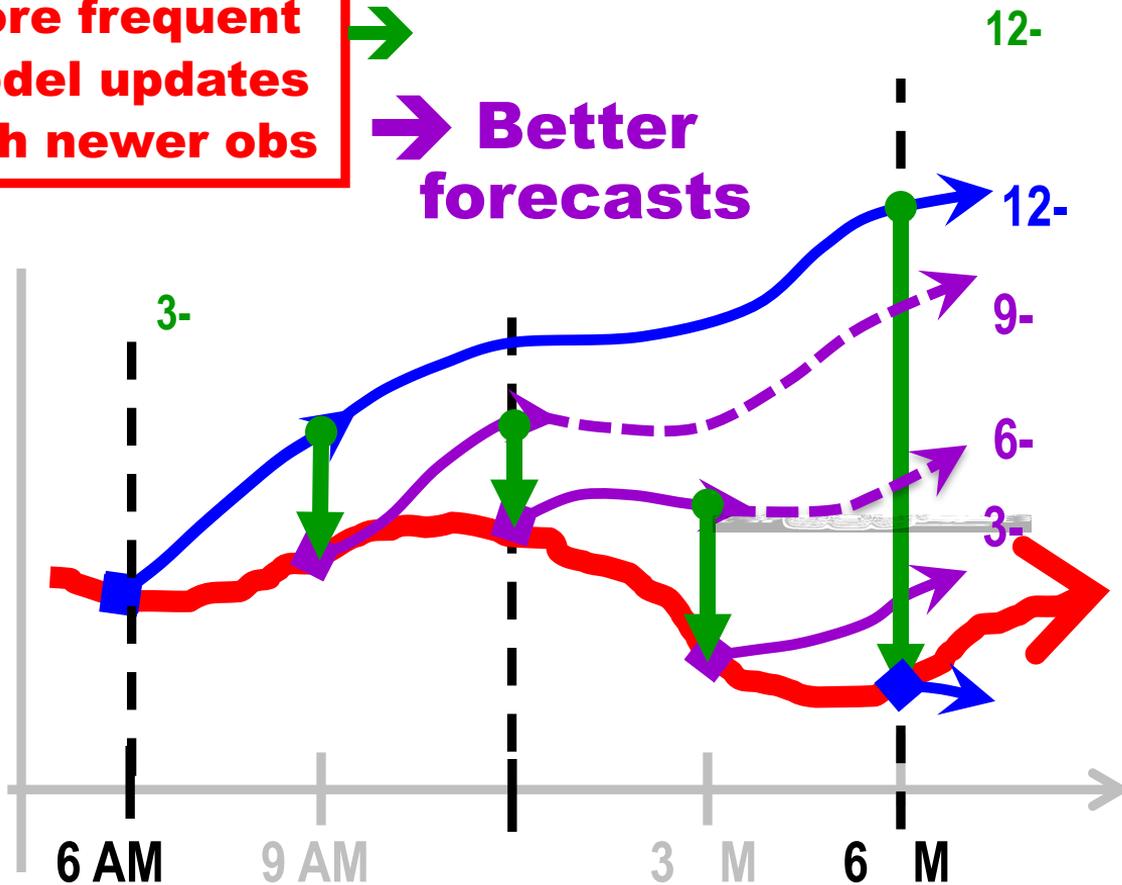




# Rapid updating – Why do it?

**More frequent  
model updates  
with newer obs**

**Better  
forecasts**



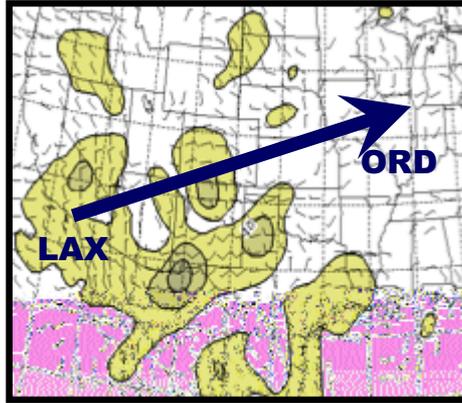
# Benefits of Rapid Cycling NWP

Rapid update cycling with latest observations improves short-range forecasts (including upper-level winds)

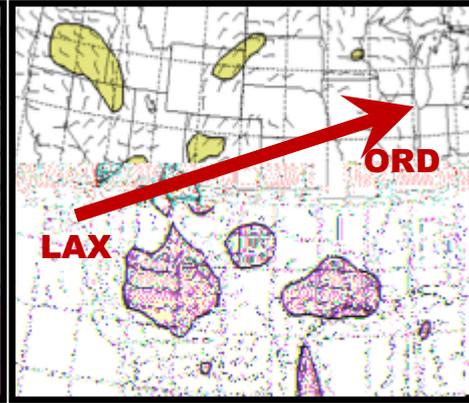
12-h fcst  
wind errors



6-h fcst  
wind errors

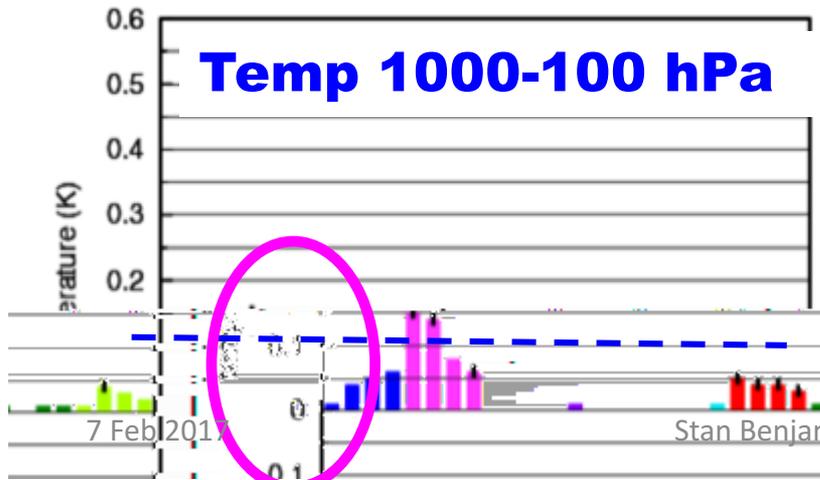
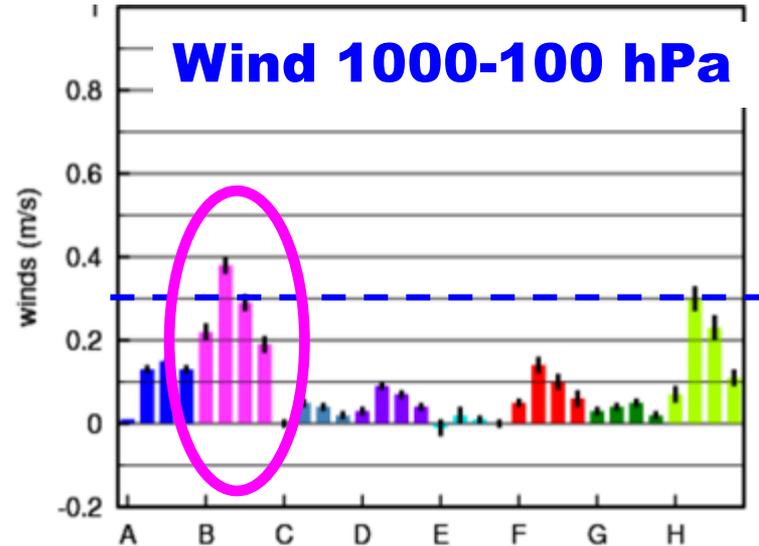
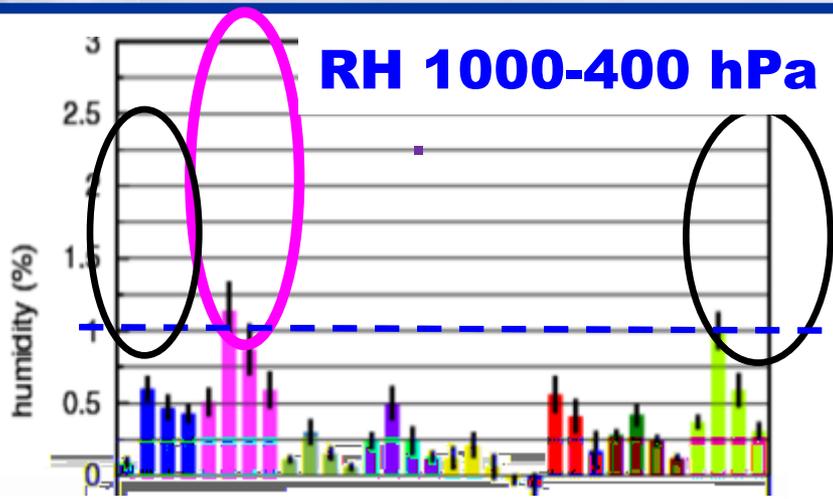


3-h fcst  
wind errors



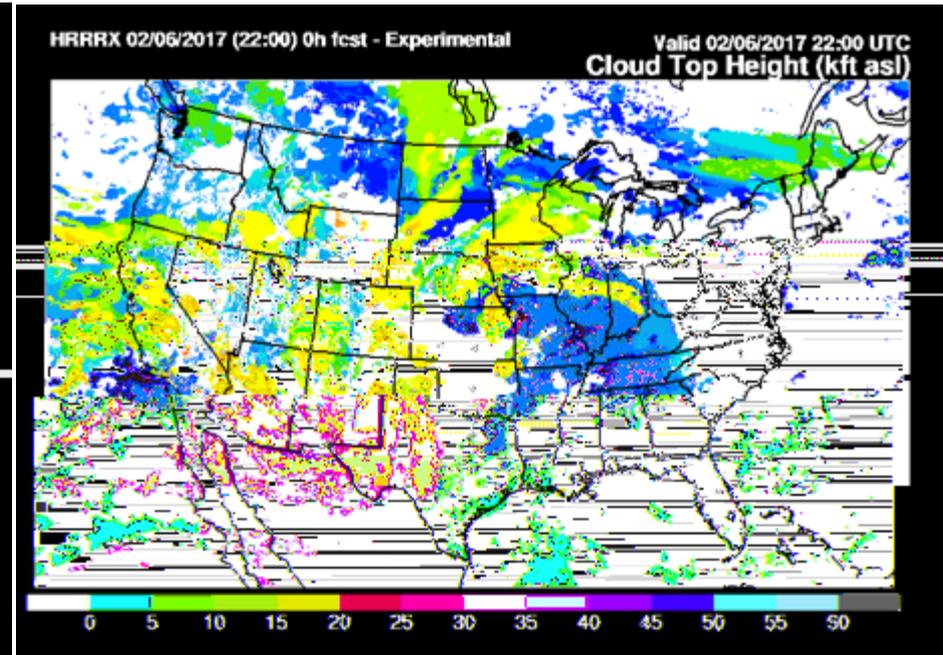
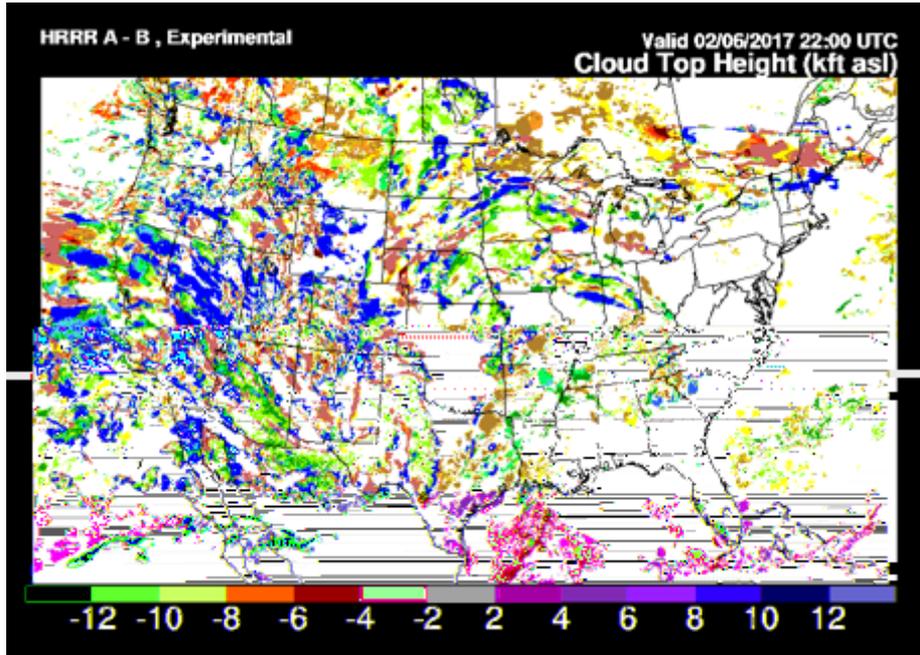
*RUC jet-level (35 kft) wind forecast errors*

# New RAP obs impact study - Aircraft most important



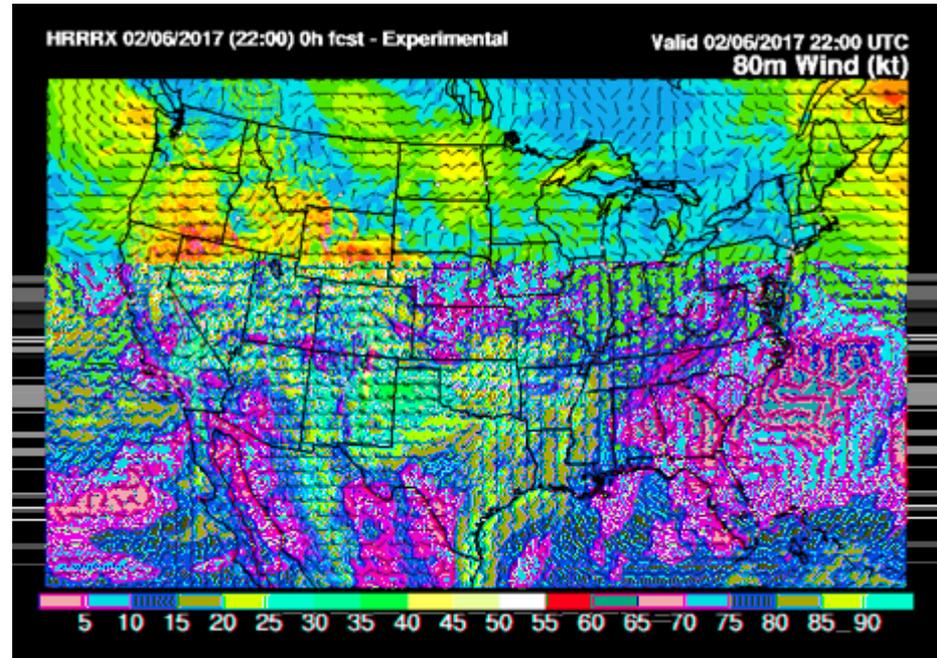
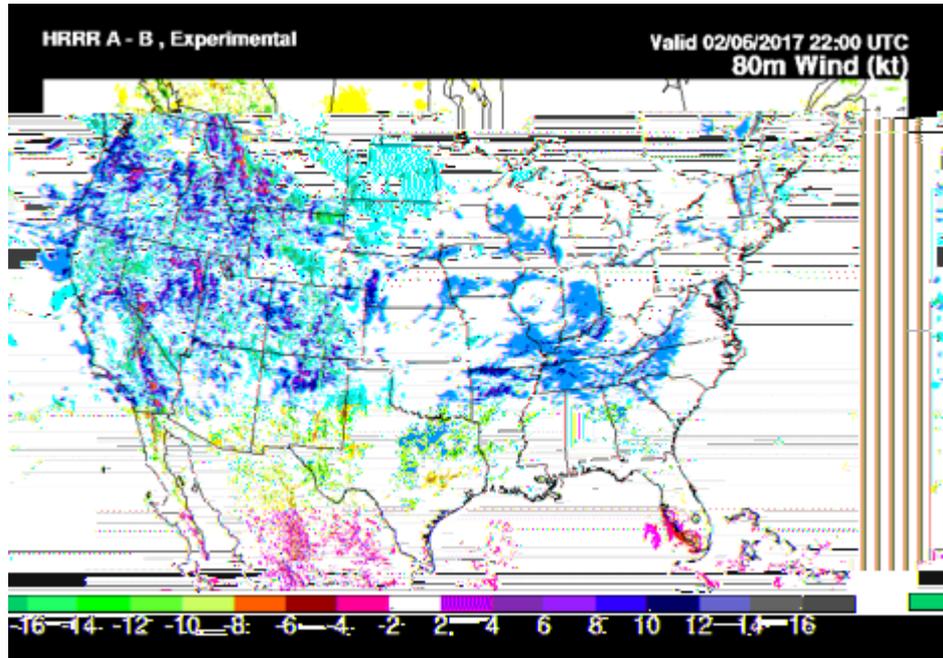
# HRRR 22z 6 Feb 2017 – cloud-top height

Analysis-background increment // Full field



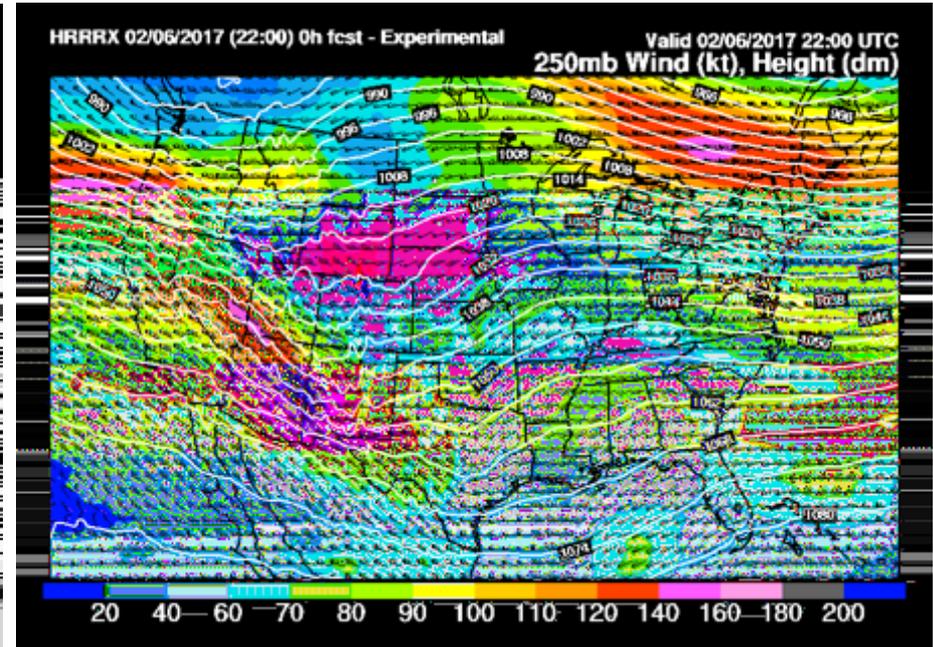
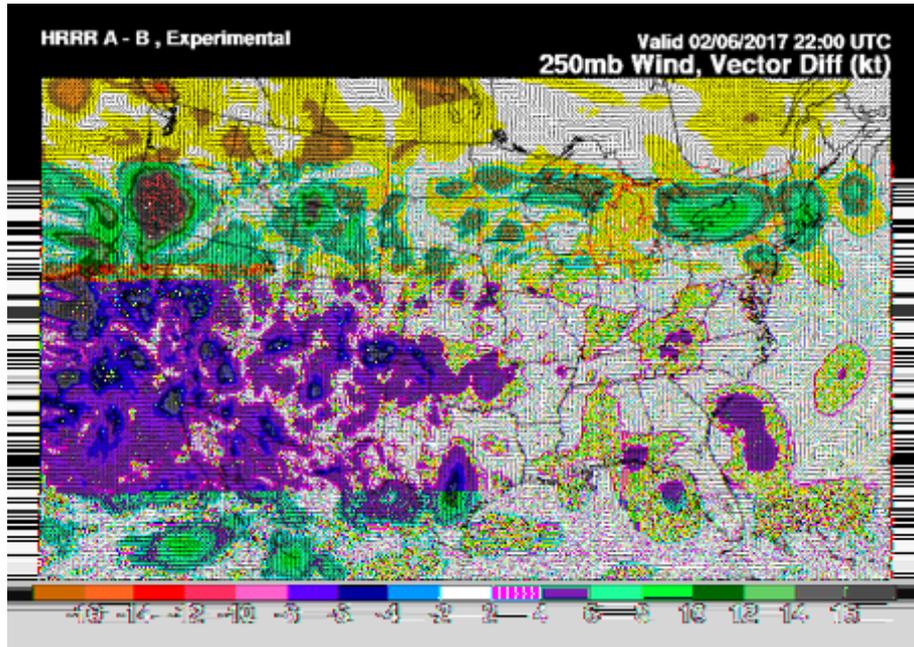
# HRRR 22z 6 Feb 2017 – 80m wind

Analysis-background increment // Full field



# HRRR 22z 6 Feb 2017 – wind – 250 hPa (~35kft)

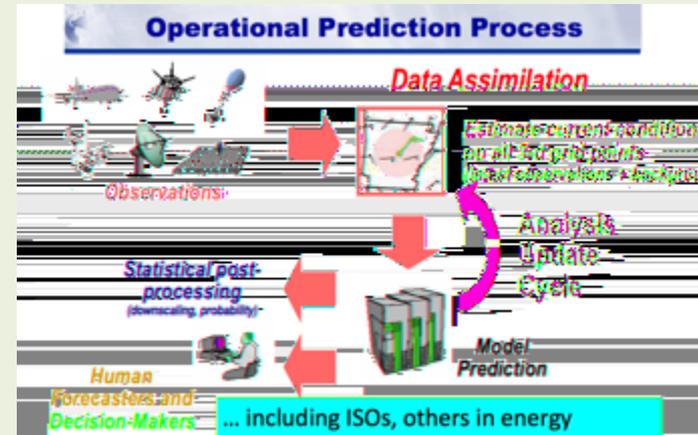
Analysis-background increment // Full field



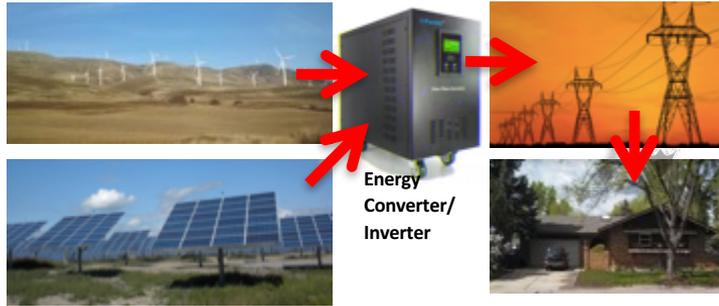
Weather is 3-D. And so are forecast errors.

# Weather models / HRRR / RE application

- How do weather models work?
- What are the unique designs of the HRRR and RAP weather models?
- **What is needed for improved models for turbine-level winds and downward solar radiation?**

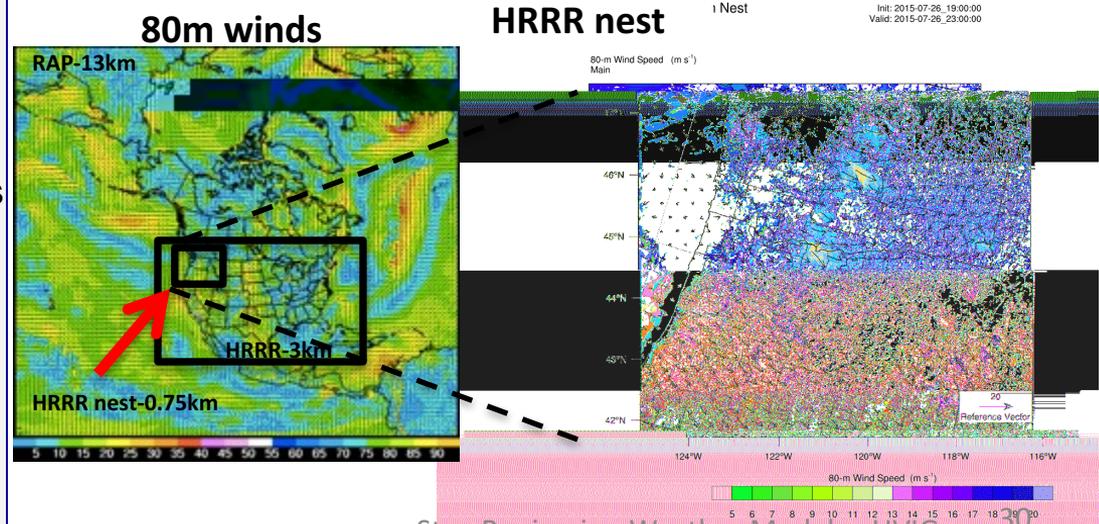


# Renewable Energy Challenges



- Wind & solar are highly variable sources of energy; *accurate forecasts are needed* to integrate wind and solar energy into the electric grid
- Reduce electricity costs (less penalties, less need for reserves)
- More stable electric grid (if forecasts are accurate)
- Reduction of CO<sub>2</sub> can mitigate climate change

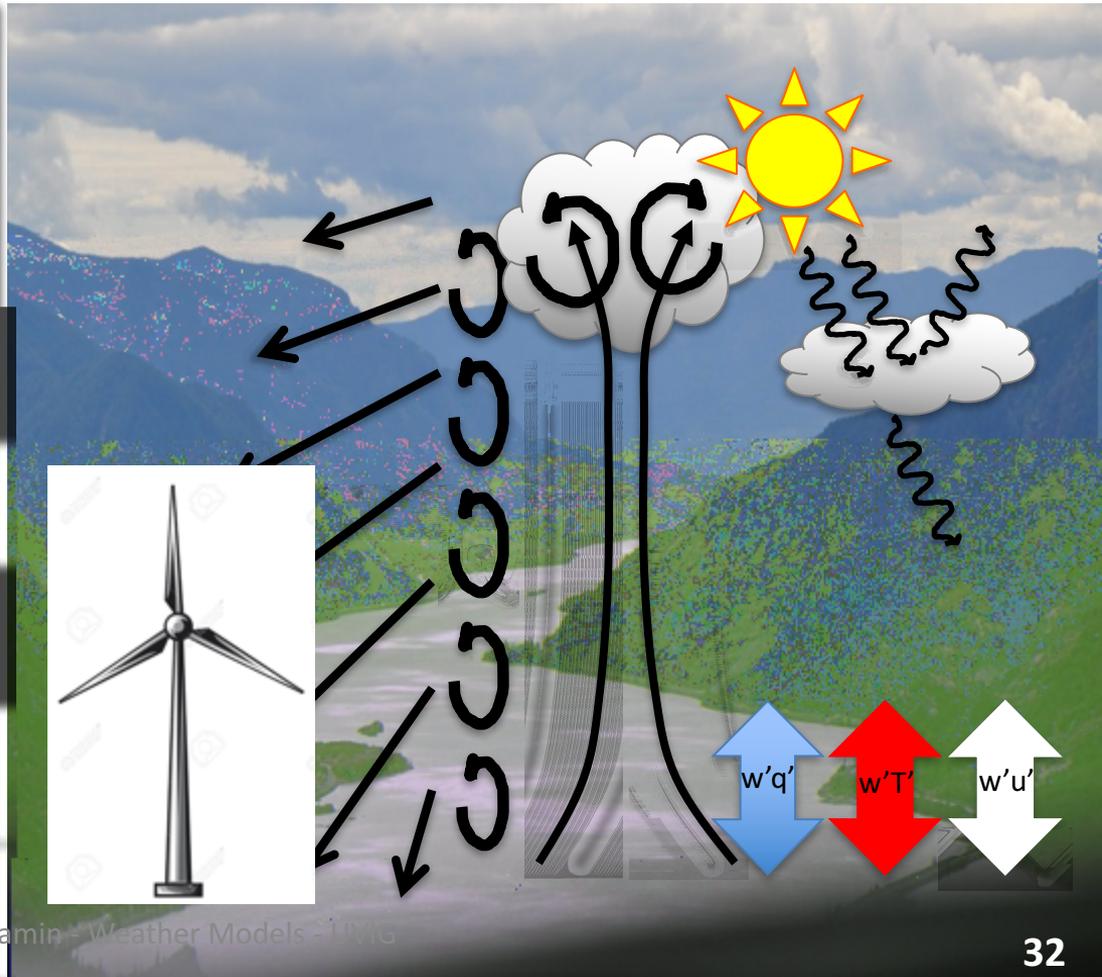
- Improve understanding of physical processes (e.g., clouds & turbulence) important for wind & solar energy.
- Improve representation of these processes in our models:
  - Improve model physical parameterization schemes
  - Improved coupling of schemes
  - Make schemes scale-aware
- Improve data assimilation of clouds, lower troposphere, PBL



# HRRR gaps for VG (RE) application

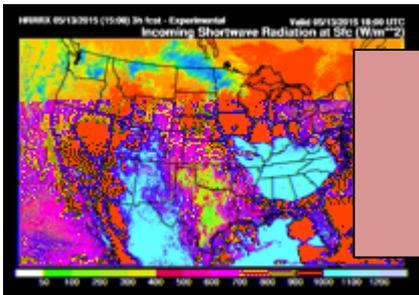
| <u>Gap</u>                                 | <u>How to address:</u>  |
|--|---|
| - doesn't cover Day-Ahead                  | - 36h forecasts every 6h in ESRL experimental HRRR  |
| - too many convective outflows             | - better in HRRRv2 via better PBL processes, radar/cloud assimilation<br>More coming in HRRRv3 – better convective environment, 3km ensemble data assimilation  |
| - too much wind at night                   | - better in HRRRv2 but still too strong.<br>More improvements (MYNN) coming in HRRRv3.  |
| - no investigation yet for complex terrain | – WFIP2 field program.  |
| - still inadequate clouds                  | - intense effort by GSD and NCAR<br>– MYNN sub-gridscale cloud treatment<br>Related to international Grey-Zone cloud modeling study.<br>- Radiation feedback from new clouds every 20s.<br>- HRRR-Smoke – improved aerosols |

| Process                       | Model Component                           | Change/Addition   |
|-------------------------------|---|---|
| Turbulent Diffusion           | MYNN PBL/<br>3d-Blended<br>TKE            | <ul style="list-style-type: none"> <li>Mixing length               <ul style="list-style-type: none"> <li>Scale-aware</li> <li>Z-less</li> </ul> </li> <li>1D → 3D as <math>f(\Delta x) \rightarrow 0</math></li> </ul> |
| Non-local Turbulent Transport | MYNN Mass-flux                            | <ul style="list-style-type: none"> <li>Multi-plume</li> <li>TKE transport</li> <li>Momentum transport</li> <li>Scale-aware</li> </ul>   |
| Surface Fluxes                | RUC LSM/<br>MYNN Sfc Layer                | <ul style="list-style-type: none"> <li>Scalar roughness</li> <li>M-O alternatives</li> <li>3D surface stress</li> </ul>   |
| <b>Clouds</b>                 | Thompson Aero/<br>Chaboureau-<br>Bechtold | <ul style="list-style-type: none"> <li>Subgrid scale clouds</li> <li>Coupled to radiation</li> <li>prognostic</li> </ul>  |
| Numerics/<br>Dynamics         | Vertical<br>Coordinate,<br>Advection      | <ul style="list-style-type: none"> <li>Hybrid Vertical<br/>Coordinate</li> <li>IBM</li> </ul>   |
| Turbine Drag                  | Wind Farm<br>Parameterization             | <ul style="list-style-type: none"> <li>Wind direction effects</li> <li>Power calculation</li> </ul>   |





14 SURFRAD / ISIS



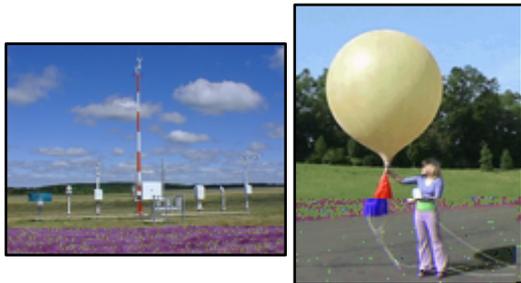
model: HRRR    station: All

scale: 13 km    avg: None    var: DSWRF (= direct+diffuse)

fcst: 1    RUN or VALID time(s):    stat: MAE (mean abs error)

Dates: 2015    Apr    13    through    2015    May    13

add curve    close plots    plot unmatched    plot matching    diffs:  2-1, 3-1,...     2-1, 4-3,...    show:  text     errors



■ NOAA/ESRL/GMD SURFRAD / ISIS

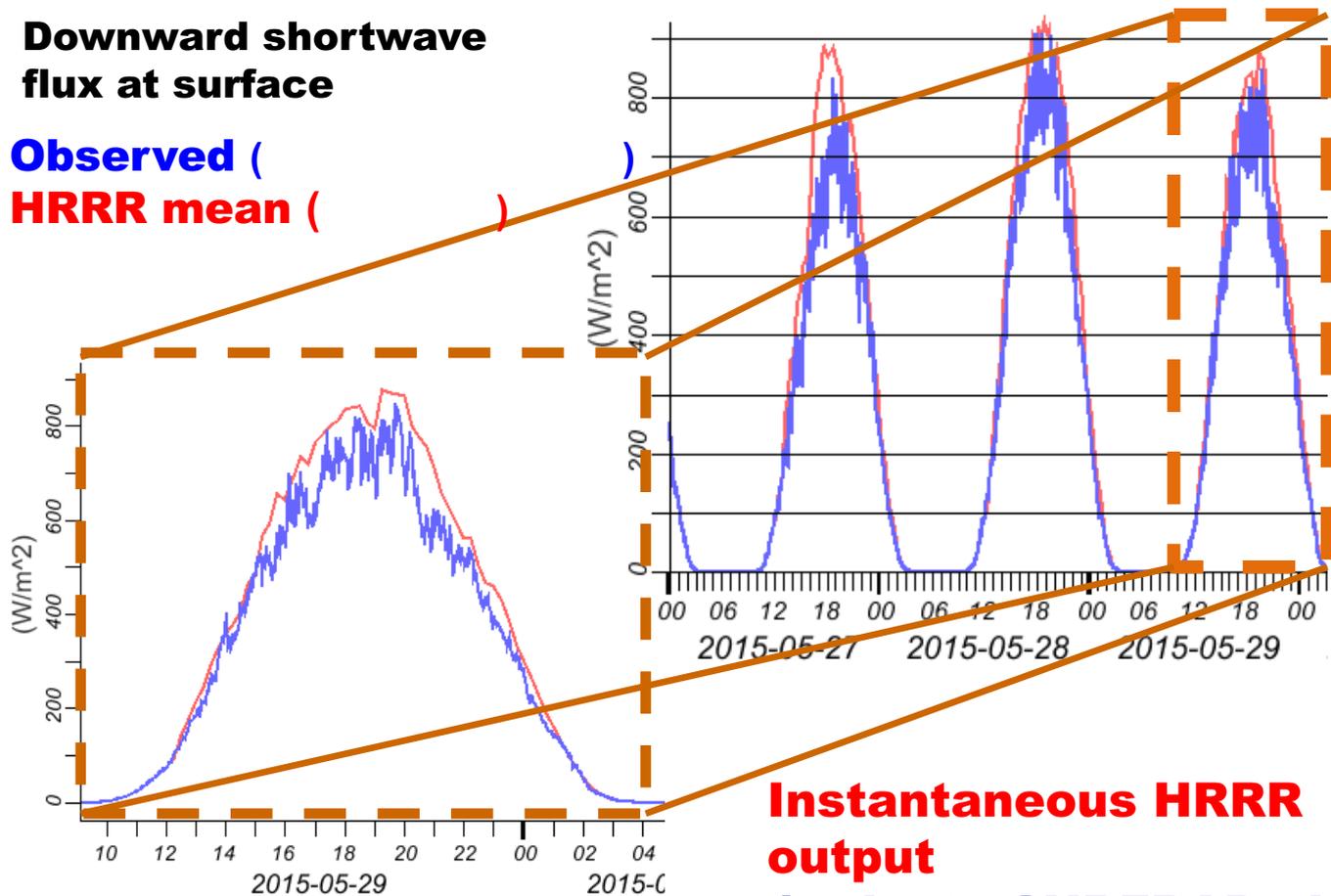
:

■ Directly quantify

issues

## Downward shortwave flux at surface

Observed ( )  
HRRR mean ( )



**Instantaneous HRRR  
output**

**1 minute SURFRAD obs**

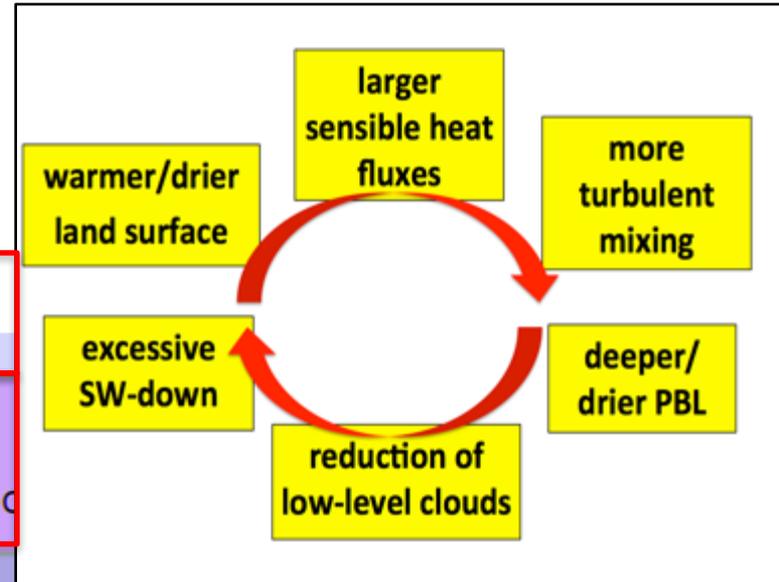
**Q:** Subgrid cloud issues even at 3km HRRR/ARW-WRF resolution?

**A:** Yes.

10% of global cloudiness <10km, below 4dx with 3km HRRR resolution

# Solutions/mitigations in HRRR/RAP model/assimilation to address warm/dry bias

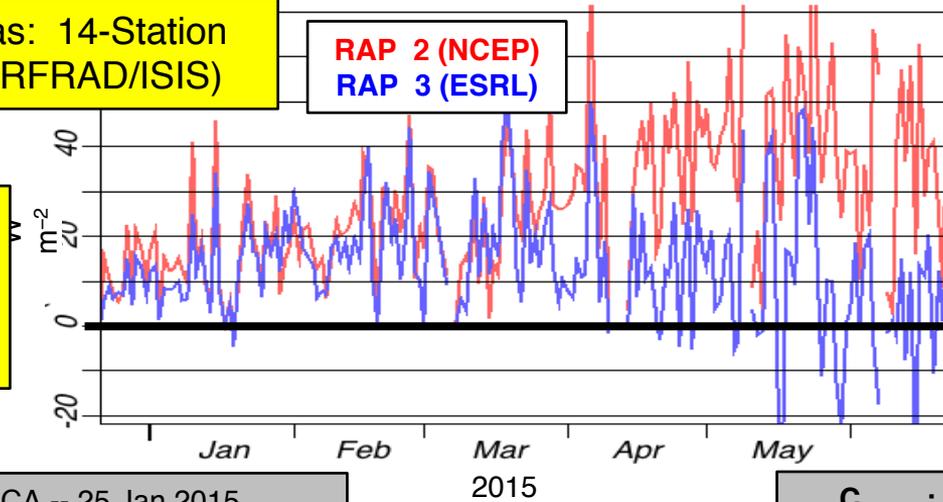
| Component  | Mitigating Items   |
|--|--|
| GSI Data Assimilation  | Canopy water cycling<br>Temp pseudo-innovations thru model boundary layer<br>More consistent use of surface temp/dewpoint data |
| GFO Convective Parameterization  | Shallow cumulus radiation attenuation<br>Improved retention of stratification atop mixed layer                                 |
| Thompson Microphysics  | Aerosol awareness for resolved cloud production<br>Attenuation of shortwave radiation  |
| Mixing length parameter changed<br>Thermal roughness in surface layer changed<br>Coupling boundary layer clouds to RRTMG radiation | MYNN Boundary Layer  |
| Reduced wilting point for more transpiration<br>Keep soil moisture in croplands above wilting point                                | RUC Land Surface Model   |



# RAP S I (GHI) B

6-h Forecast Bias: 14-Station  
Daily Mean (SURFRAD/ISIS)

RAP 2 (NCEP)  
RAP 3 (ESRL)



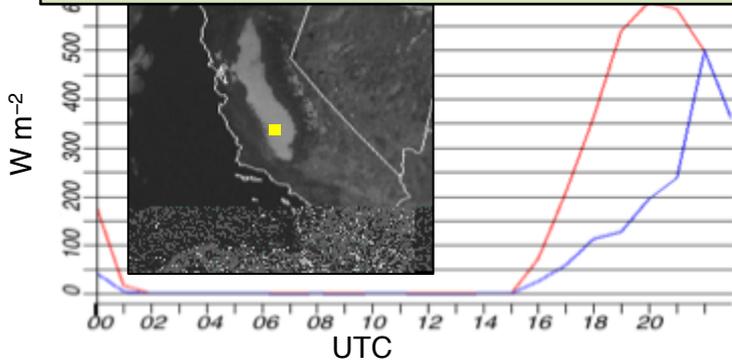
*Improvement in  
RAPv3 cloudiness....  
But still some ways to  
go.*



Shallow Cumulus

**S** : Hanford, CA -- 25 Jan 2015

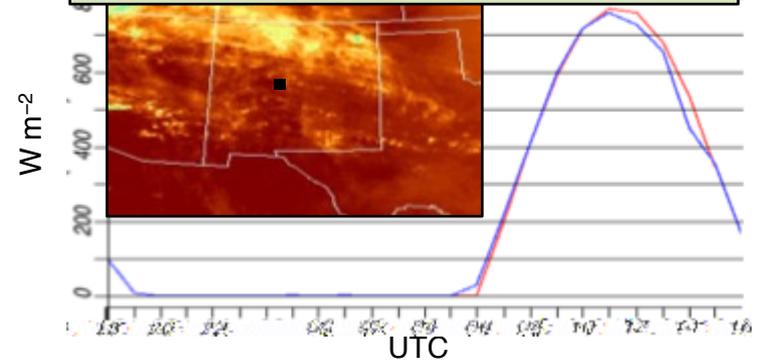
KVIS 251835Z AUTO 0000KT 1/4SM **OVC002**



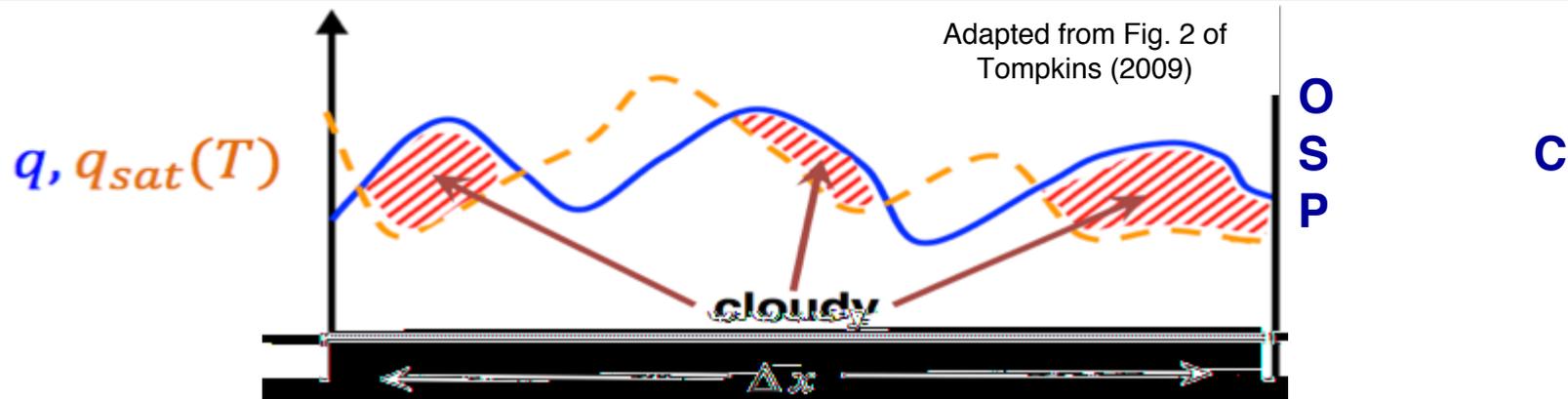
6- F : RAP 3  
M : ISIS

**C** : Albuquerque, NM -- 19 Feb 2015

KABQ 192052Z 21005KT 10SM **SCT250**



# I : T I S - C



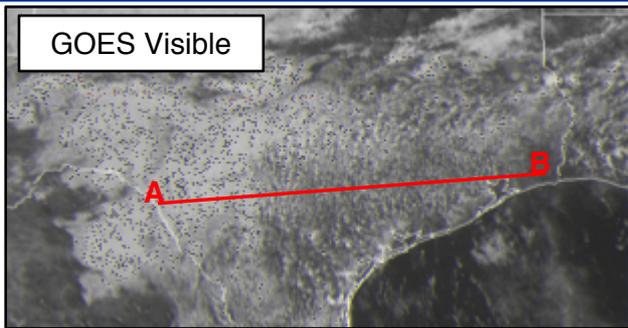
$$Var(s) \propto Var(q) + Var(T) - Cov(q, T)$$

A PDF  $s$   
(saturation ratio)

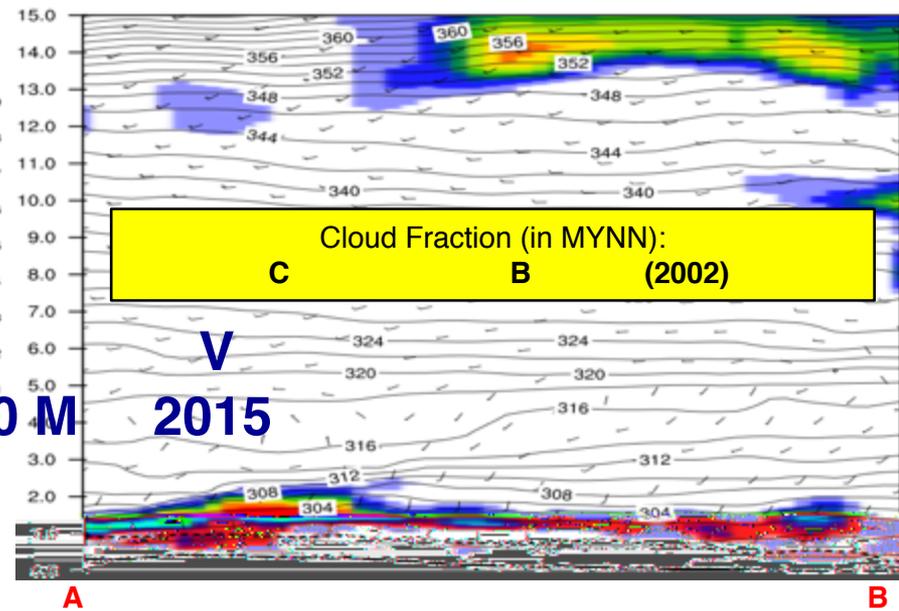
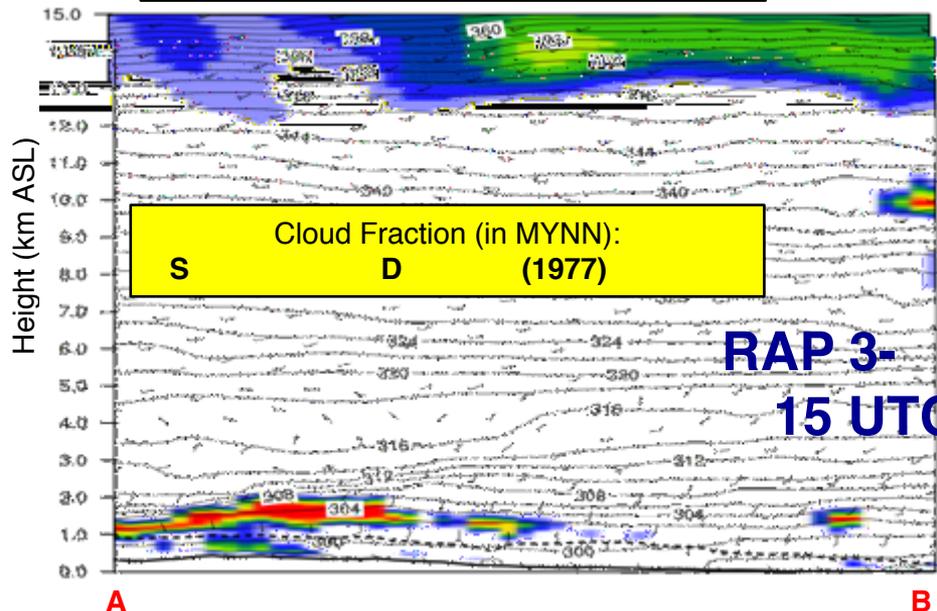
R C F ,  
C C

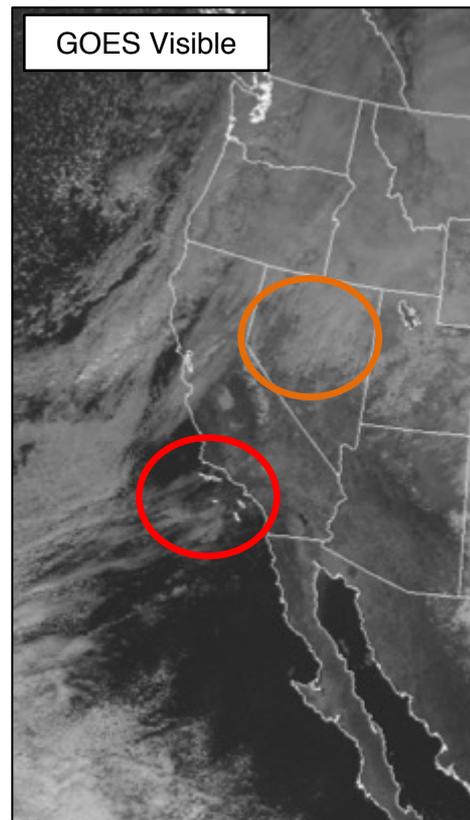
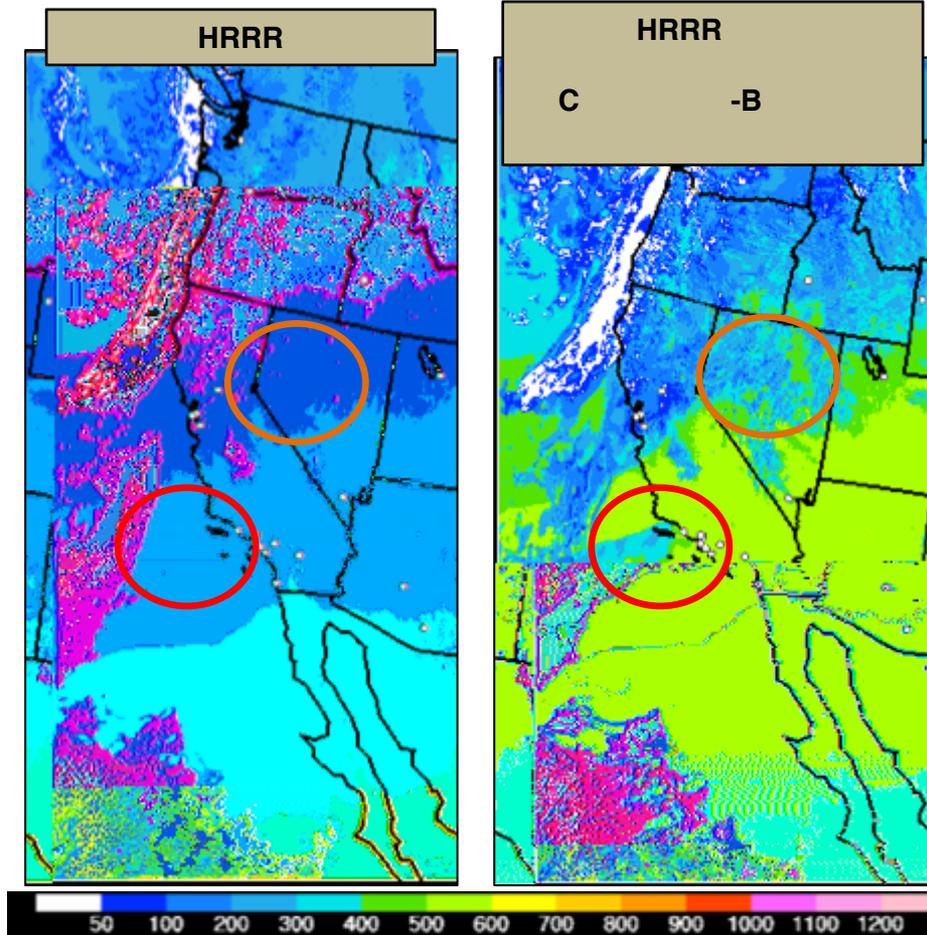
assume P :  
PDF

- S D (1977) M (1977)
- Gaussian joint distributions
- C B (2002)
- Allows for skewed distributions
  - May be implemented diagnostically or prognostically



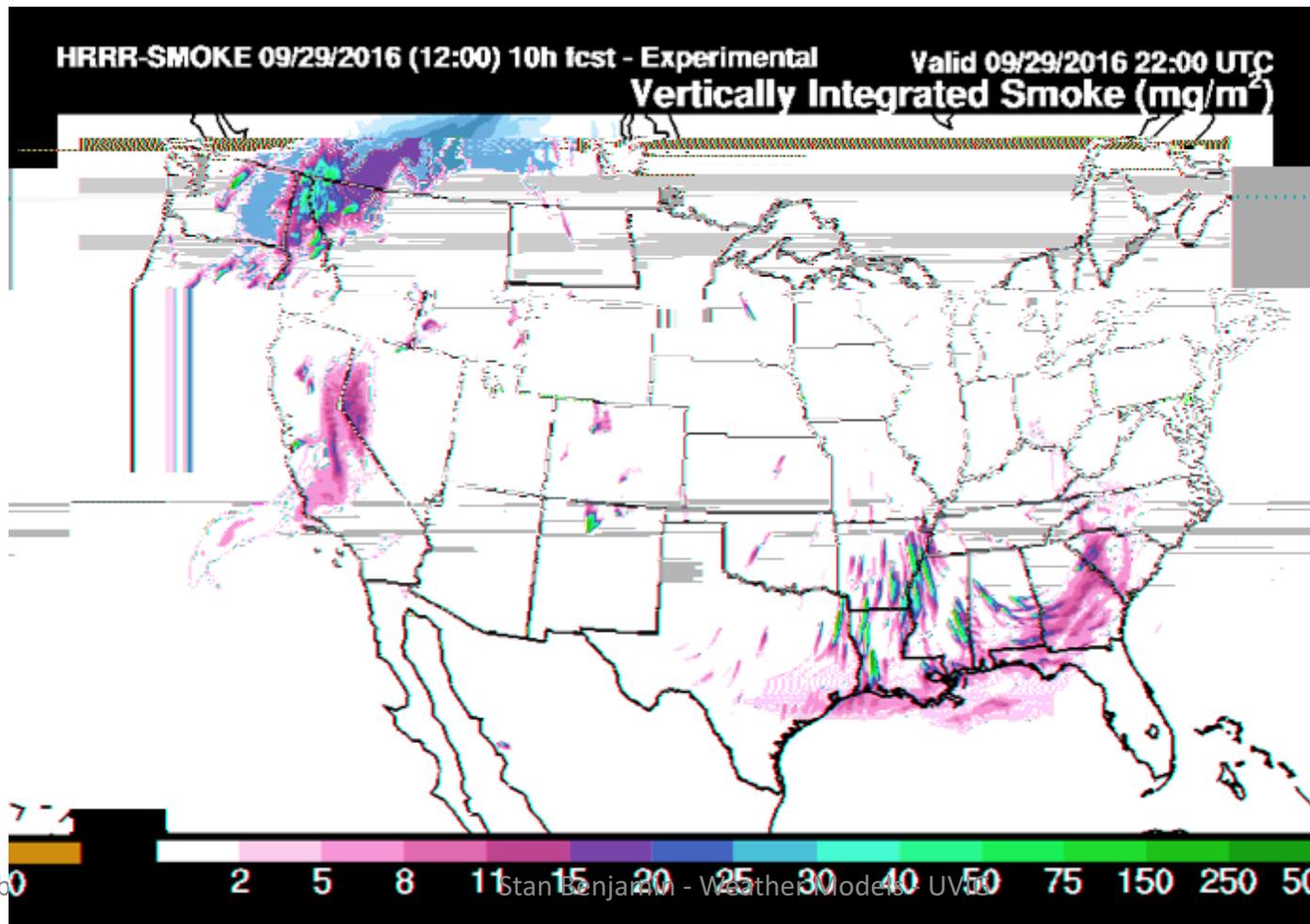
- Chaboureau and Bechtold (2002) scheme is “active” in stratocumulus, cumulus, and cirrus regions
- Better able to represent low–intermediate cloud fractions





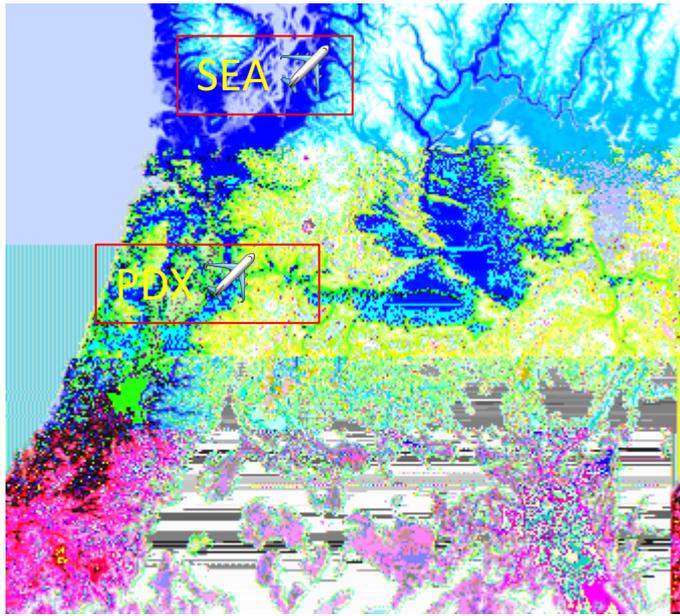
- Chaboureau and Bechtold (2002) scheme provides additional source of subgrid clouds for radiative flux forecasts

# HRRR-Smoke: VIIRS Fire Power, 2 prog aerosols



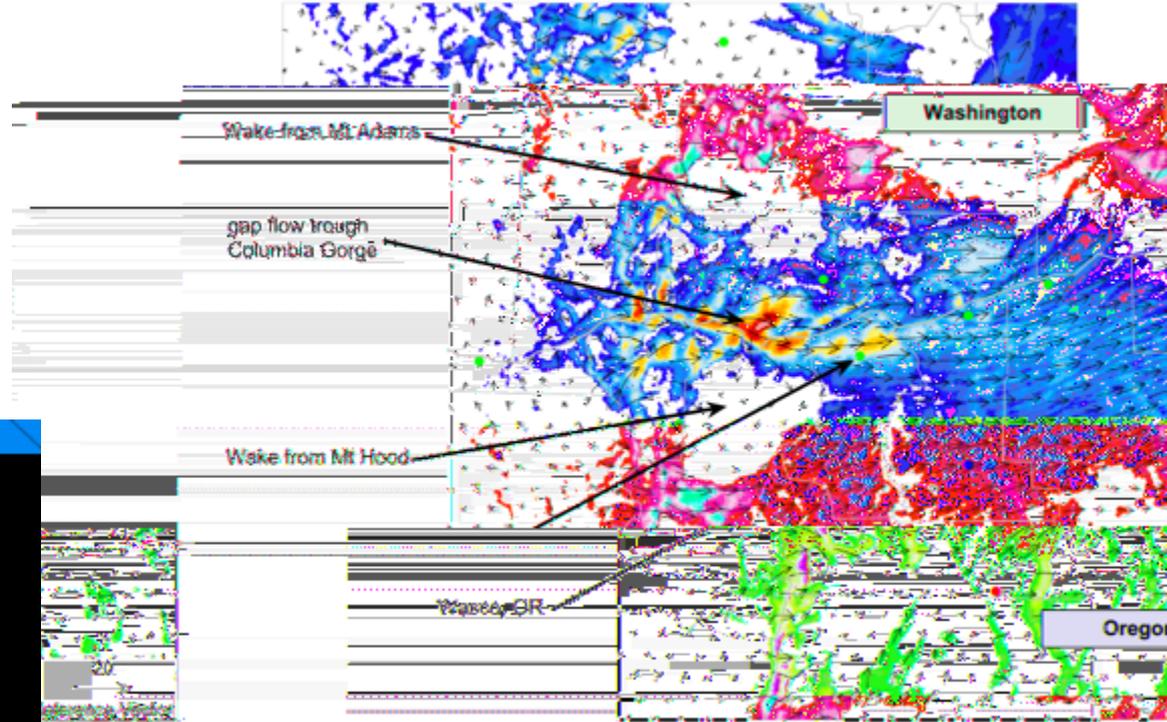
# HRRR-WFIP2

## Proving Ground for improving PBL/cloud physics



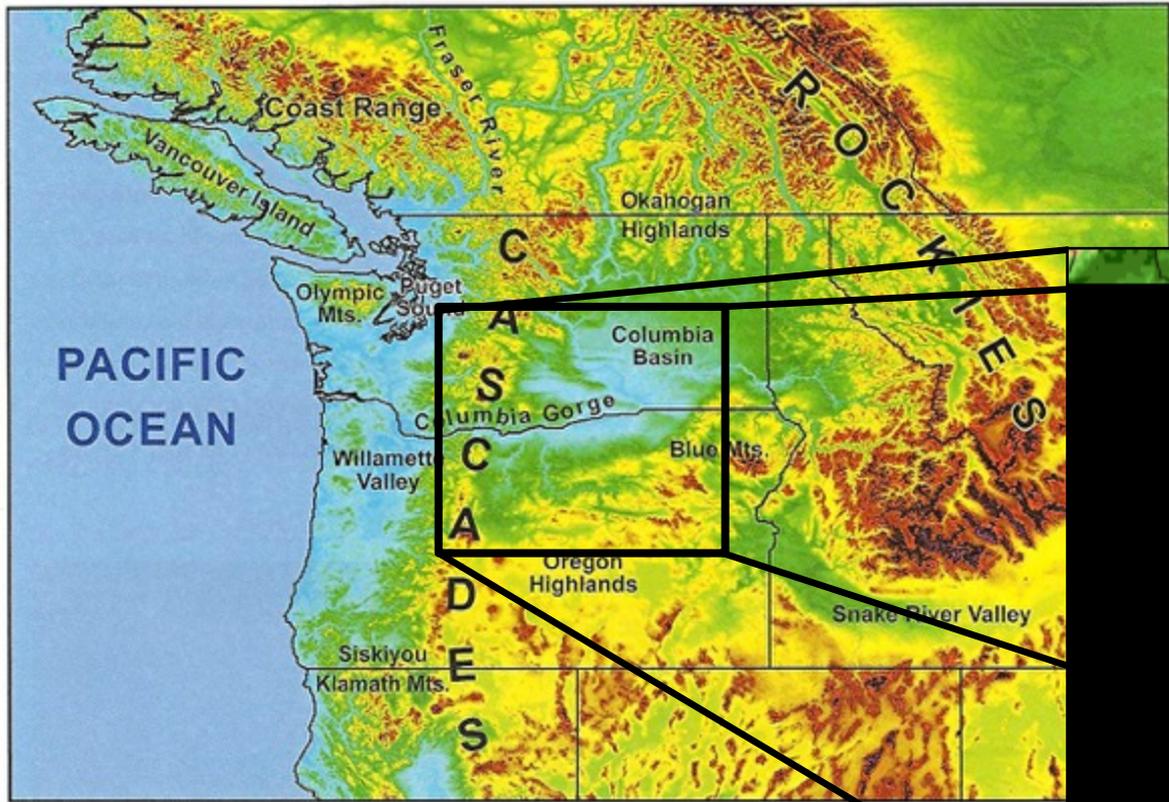
HRRR-WFIP2 750-m Nest  
80-m Wind Speed ( $\text{m s}^{-1}$ )

Init: 2015-12-15\_19:00:00  
Valid: 2015-12-15\_22:00:00



750m HRRR  
WFIP2 nest

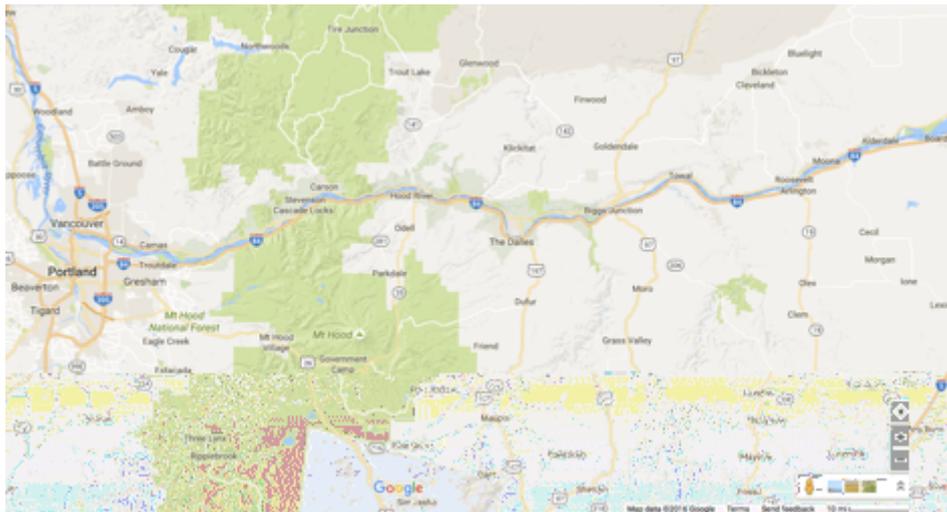
3km HRRR  
US domain



WFIP2 S R

# 750-m HRRR Nest

<http://rapidrefresh.noaa.gov/HRRRwfipsubh/>

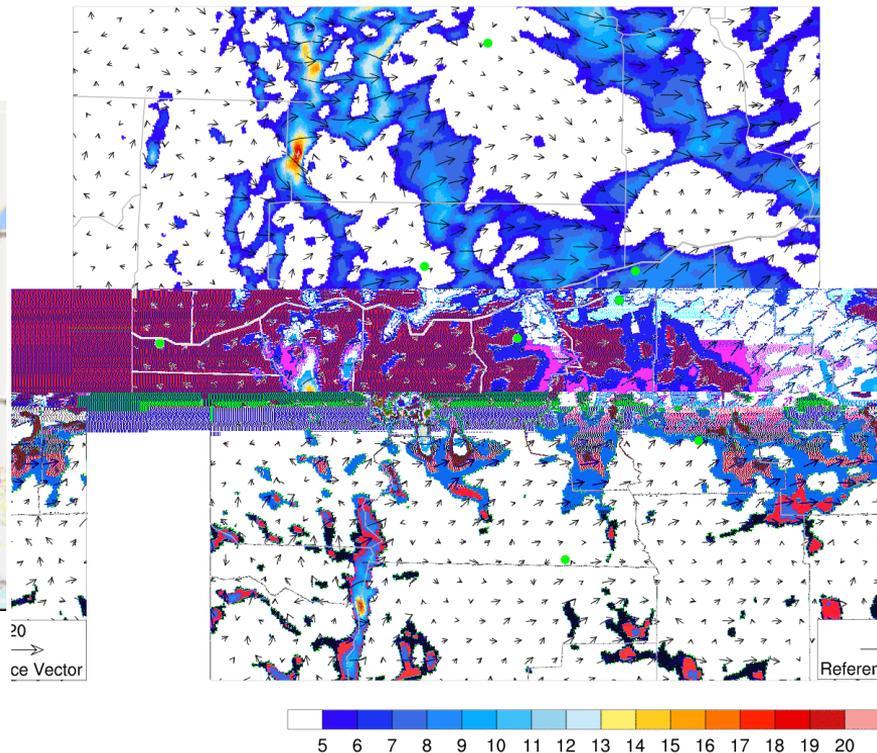


## HRRR-WFIP2 750-m Nest

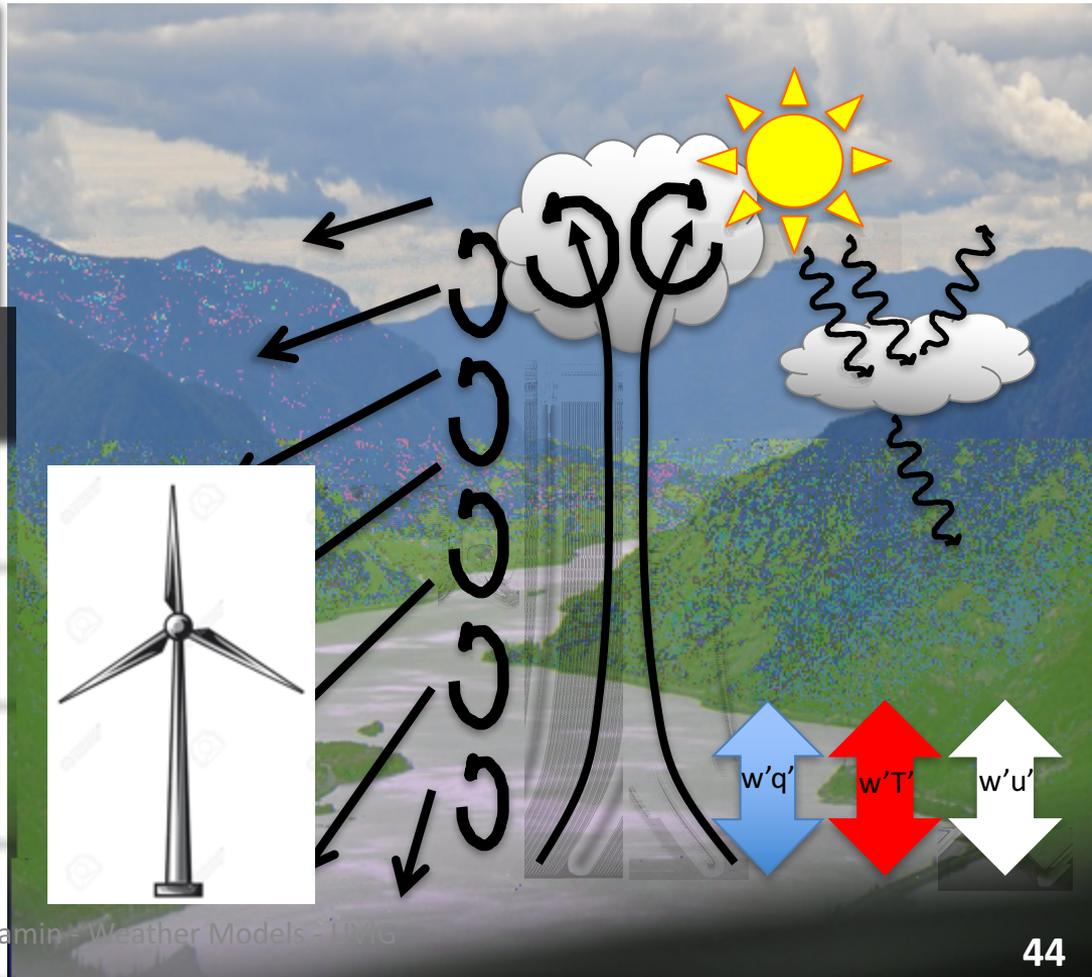
Init: 2016-03-16\_07:00:00

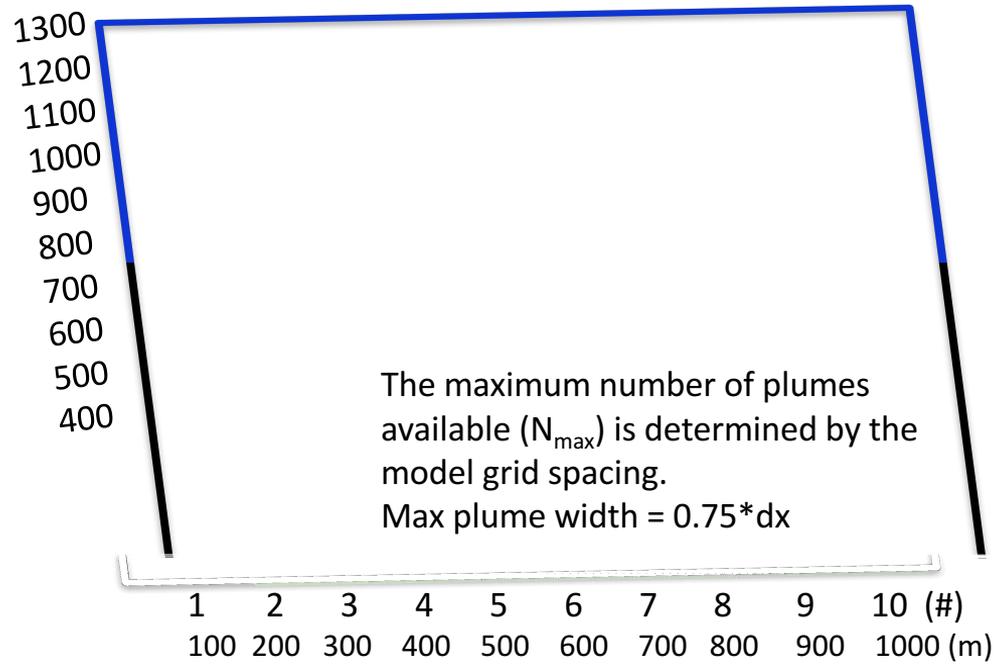
80-m Wind Speed ( $m s^{-1}$ )

Valid: 2016-03-16\_07:00:00



| Process                       | Model Component                           | Change/Addition  |
|-------------------------------|---|--|
| Turbulent Diffusion           | MYNN PBL/<br>3d-Blended<br>TKE            | <ul style="list-style-type: none"> <li>Mixing length               <ul style="list-style-type: none"> <li>Scale-aware</li> <li>Z-less</li> </ul> </li> <li>1D <math>\rightarrow</math> 3D as <math>f(\Delta x) \rightarrow 0</math></li> </ul> |
| Non-local Turbulent Transport | MYNN Mass-flux                            | <ul style="list-style-type: none"> <li>Multi-plume</li> <li>TKE transport</li> <li>Momentum transport</li> <li>Scale-aware</li> </ul>  |
| Surface Fluxes                | RUC LSM/<br>MYNN Sfc Layer                | <ul style="list-style-type: none"> <li>Scalar roughness</li> <li>M-O alternatives</li> <li>3D surface stress</li> </ul>  |
| Clouds                        | Thompson Aero/<br>Chaboureau-<br>Bechtold | <ul style="list-style-type: none"> <li>Subgrid scale clouds</li> <li>Coupled to radiation</li> <li>prognostic</li> </ul>   |
| Numerics/<br>Dynamics         | Vertical<br>Coordinate,<br>Advection      | <ul style="list-style-type: none"> <li>Hybrid Vertical<br/>Coordinate</li> <li>IBM</li> </ul>  |
| Turbine Drag                  | Wind Farm<br>Parameterization             | <ul style="list-style-type: none"> <li>Wind direction effects</li> <li>Power calculation</li> </ul>  |



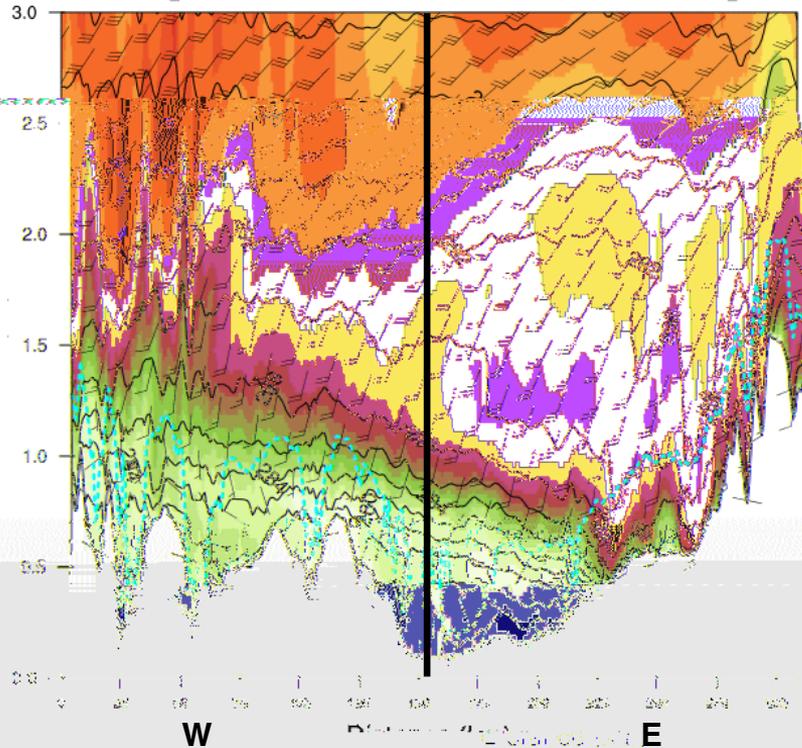


# HRRR-WFIP2 750- N F

WIND SPEED (fill), POTL TEMP (red), PBL TOP (dash)

Init: 2015-12-18\_07:00:00

Valid: 2015-12-18\_08:00:00



C P : B , OR

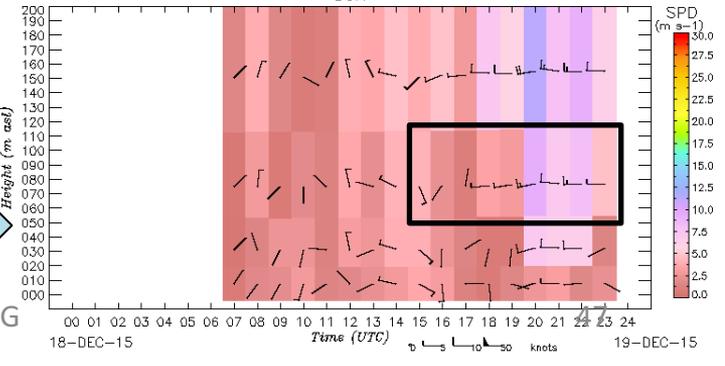
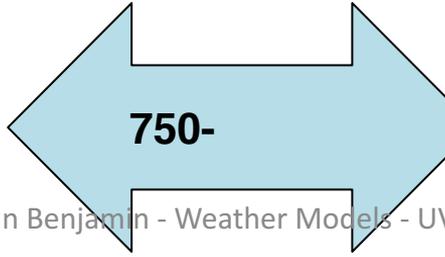
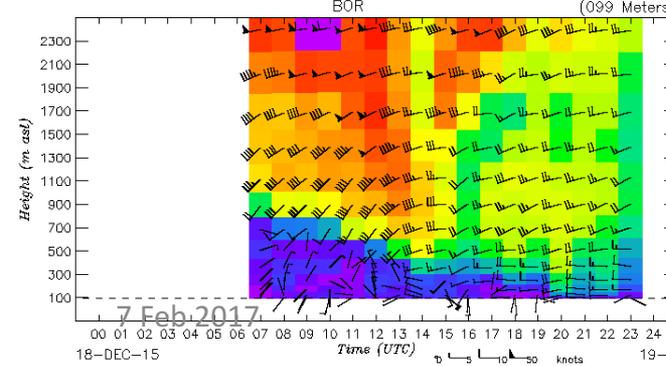
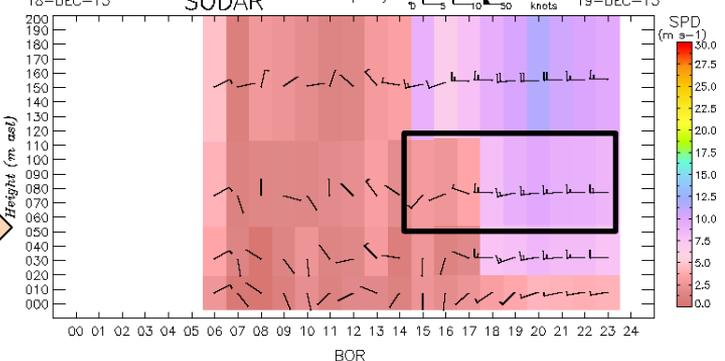
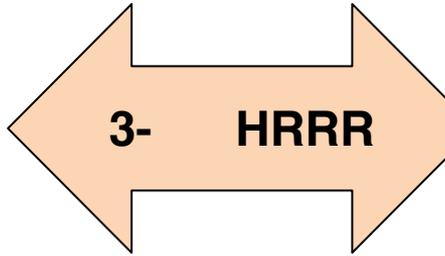
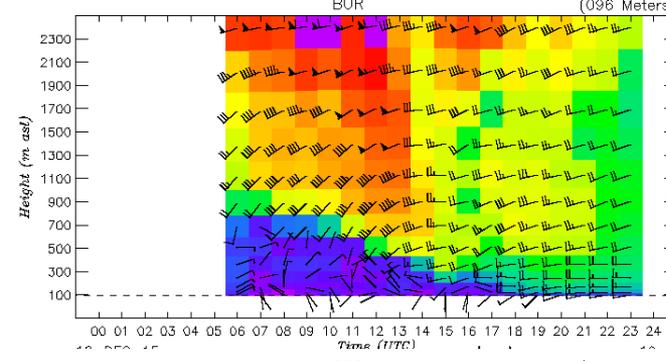
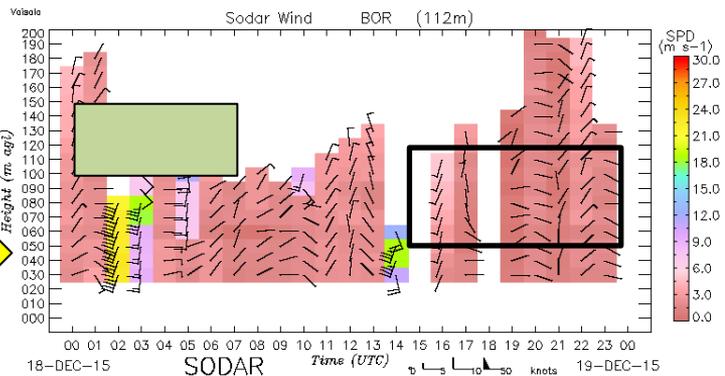
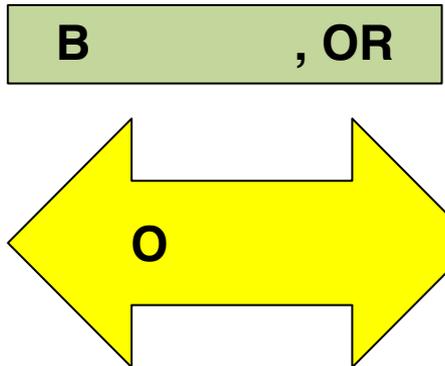
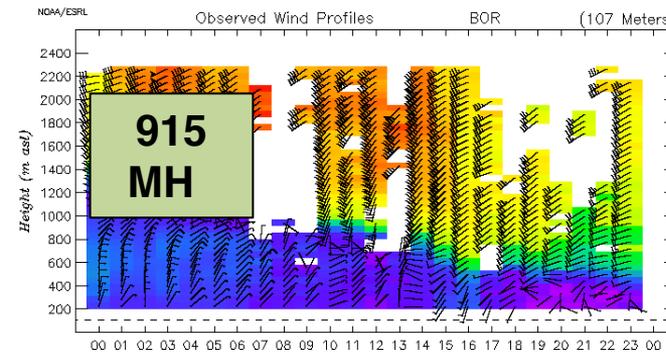
HRRR-WFIP2 750-m Nest

Init: 2015-12-18\_07:00:00

750-m Wind Speed (m s<sup>-1</sup>)

Valid: 2015-12-18\_08:00:00



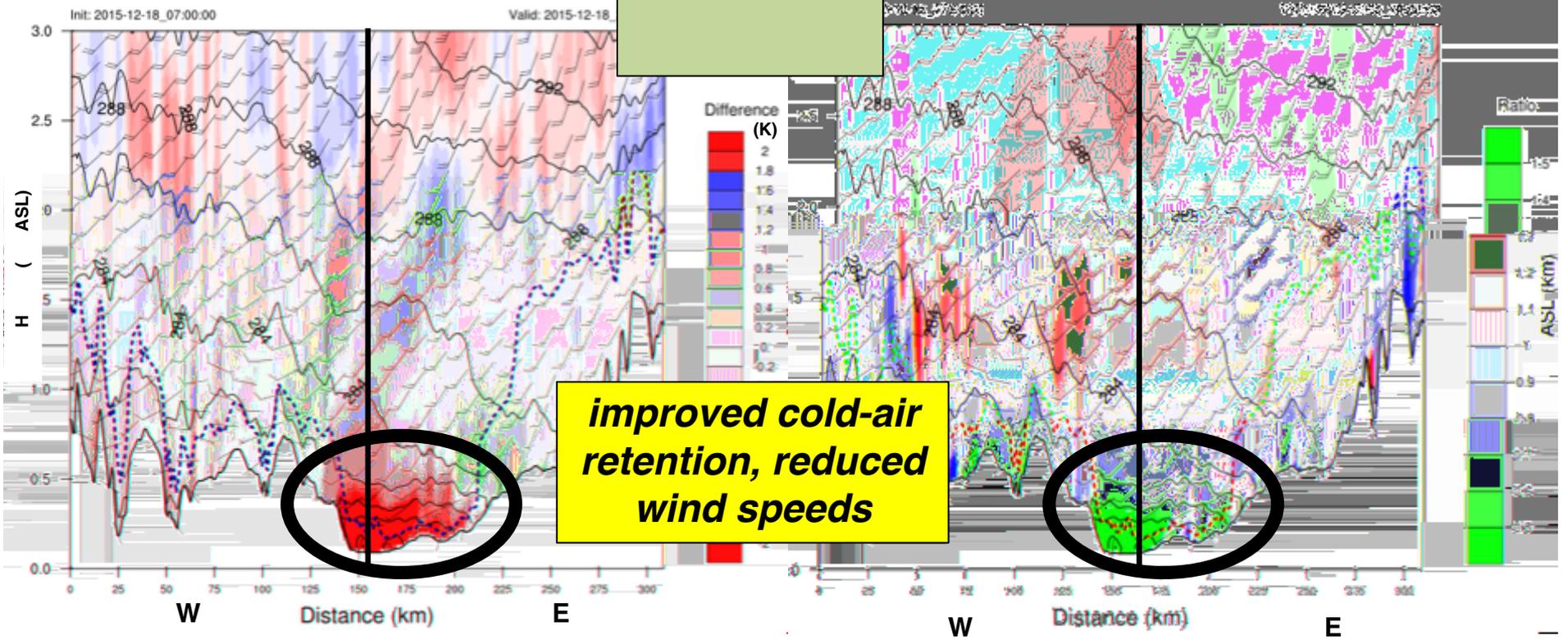


M -L R : 14- F D

T D

750-

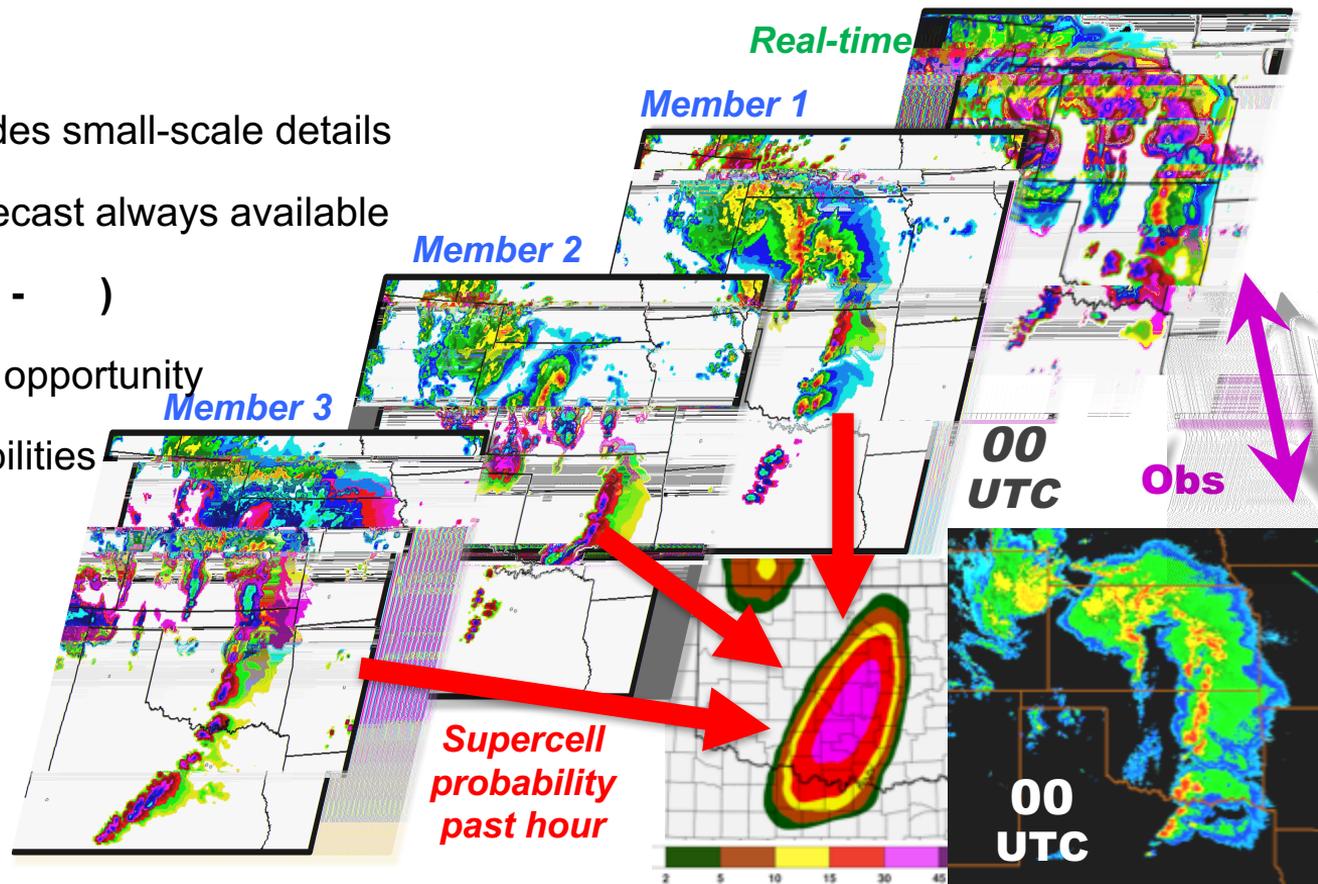
W -S R



*improved cold-air retention, reduced wind speeds*

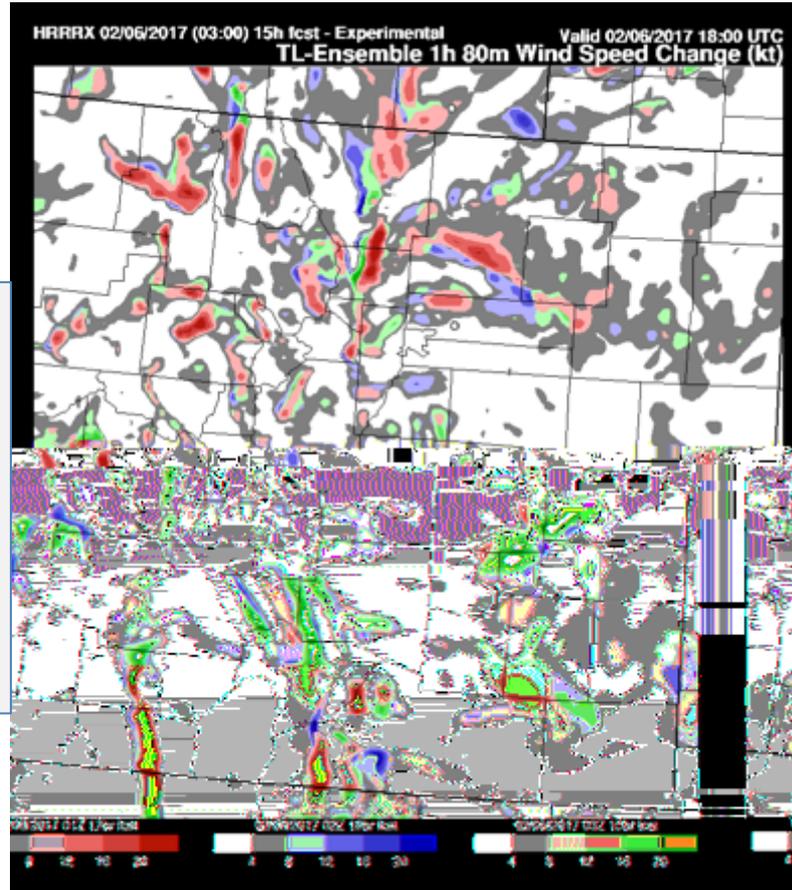
# HRRR Time-Lagged Ensemble (HRRR-TLE)

- High-resolution forecast provides small-scale details
- Hourly-updating with fresh forecast always available
  - ( - )
- Leverage runs in ensemble of opportunity
- Form hazard likelihood probabilities
- Less small-scale detail
- Proxy for confidence/certainty
- Underdispersive
  - ( )
- More expensive ensemble
- More spread/dispersive/skill



# Preliminary HRRR-TLE ramp product

80m wind ramp events valid 18z 6 Feb 2017  
- from 3 consecutive HRRR runs (03, 02, 01z) valid at same time



**HRRR-TLE – will apply also to 80m wind, downward solar**

- Common model failure mode...  
*poor representation of stable-air  
“mix out”*
  - Better representation of free-atmosphere & PBL turbulence



- For MYNN applications in 3-km HRRR and 750-m nest, reformulating the mixing-length scale appears to improve wind-forecast accuracy.
  - (1) invoke component length scales where they are physically applicable
  - (2) modify the buoyancy length scale (generally more restrictive)
- **GOAL: At same time, maintain current skill cloud/80m wind, aviation, severe weather forecast skill in all parts of US.**



# RAP / HRRR: Implementation Schedule

## RAPv3 – Implemented at NCEP August 2016

- Improved PBL, LSM, cu-parm, DA
- Thompson/NCAR aerosol-aware microphysics

Reduced warm / dry bias

## HRRRv2 – Implemented at NCEP August 2016

- Initialized by RAP (v3)
- Improved radar assimilation, hybrid assimilation, PBL/cloud physics

Improved convection

## RAPv4 – GSD testing 2016 /17



- 3D cloud fraction, better coupling to radiation scheme, better ceiling

NCEP Implement early 2018

## HRRRv3 – GSD testing 2016 /17



- **Cycled storm-scale ensemble DA**
- Cycling of aerosols with fire/emissions

NCEP Implement early 2018

## HRRRE / HREFv3 – GSD testing in 2017



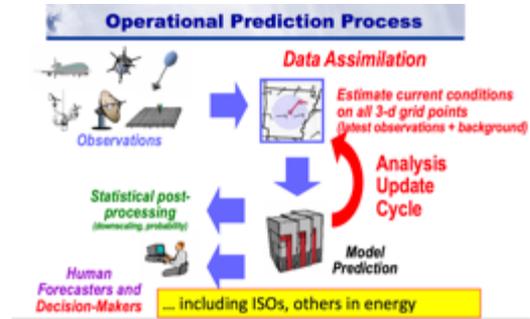
- **Storm-scale ensemble forecast component**

NCEP implement in 2019?

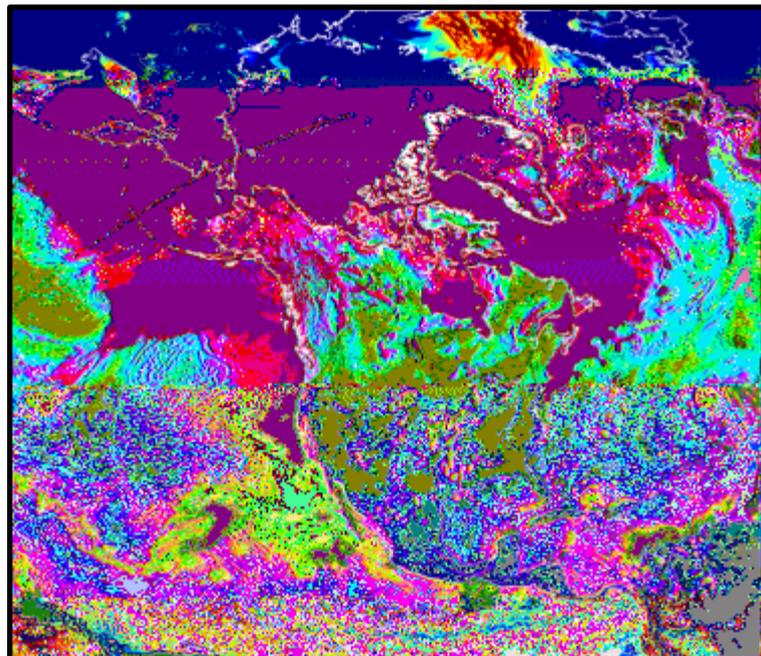
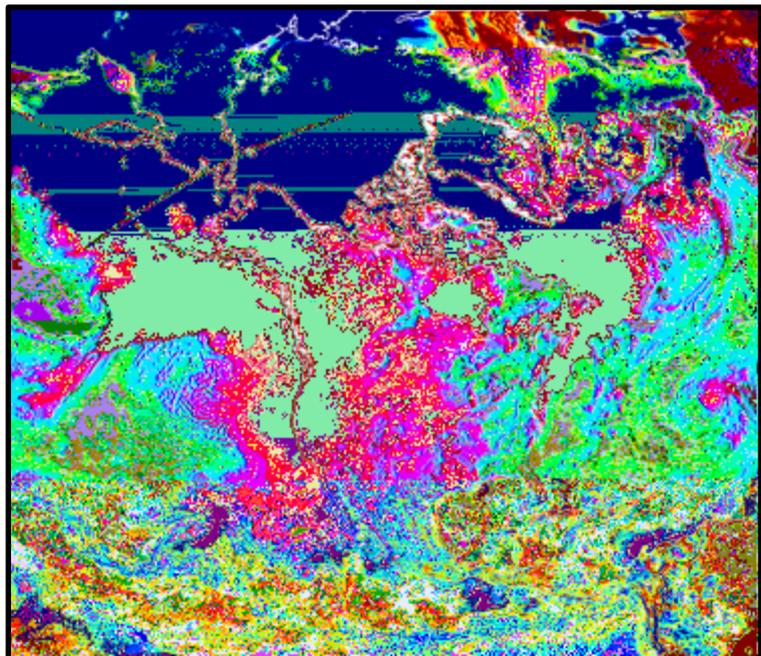


# What is still needed for improved wind/solar forecasts?

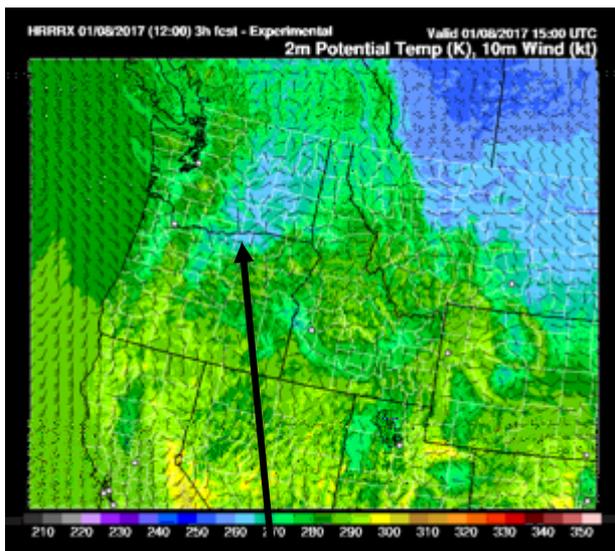
- Improved model representation boundary-layer mixing and clouds.
- Improved data assimilation and improved 3-d observations over large multi-state areas.
- Probabilistic information for decision making – from multiple ensemble members and from spatial and temporal averaging.



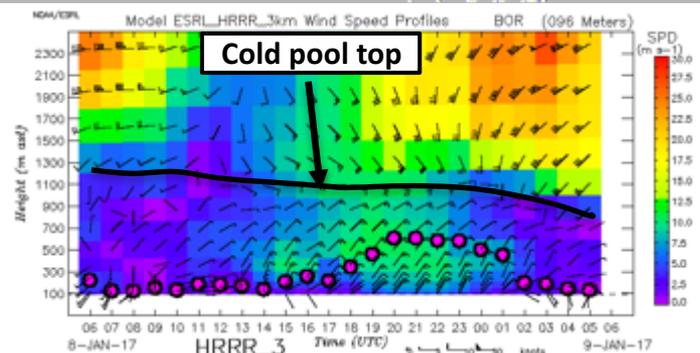
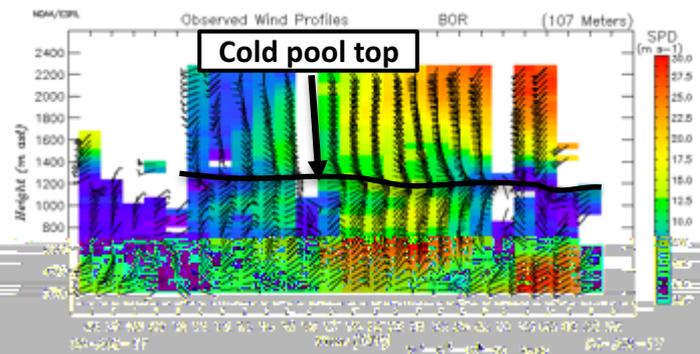




- The addition of the dynamic multi-plume mass-flux scheme improves the representation of non-local mixing in the convective boundary layer; however...



Boardman, OR



- The eddy diffusivity part of ED-MF is responsible for the stable boundary layer.
- The mixing length are important in regulating the diffusivity.
- Need a robust mixing length to regulate the diffusion within and outside the PBL.

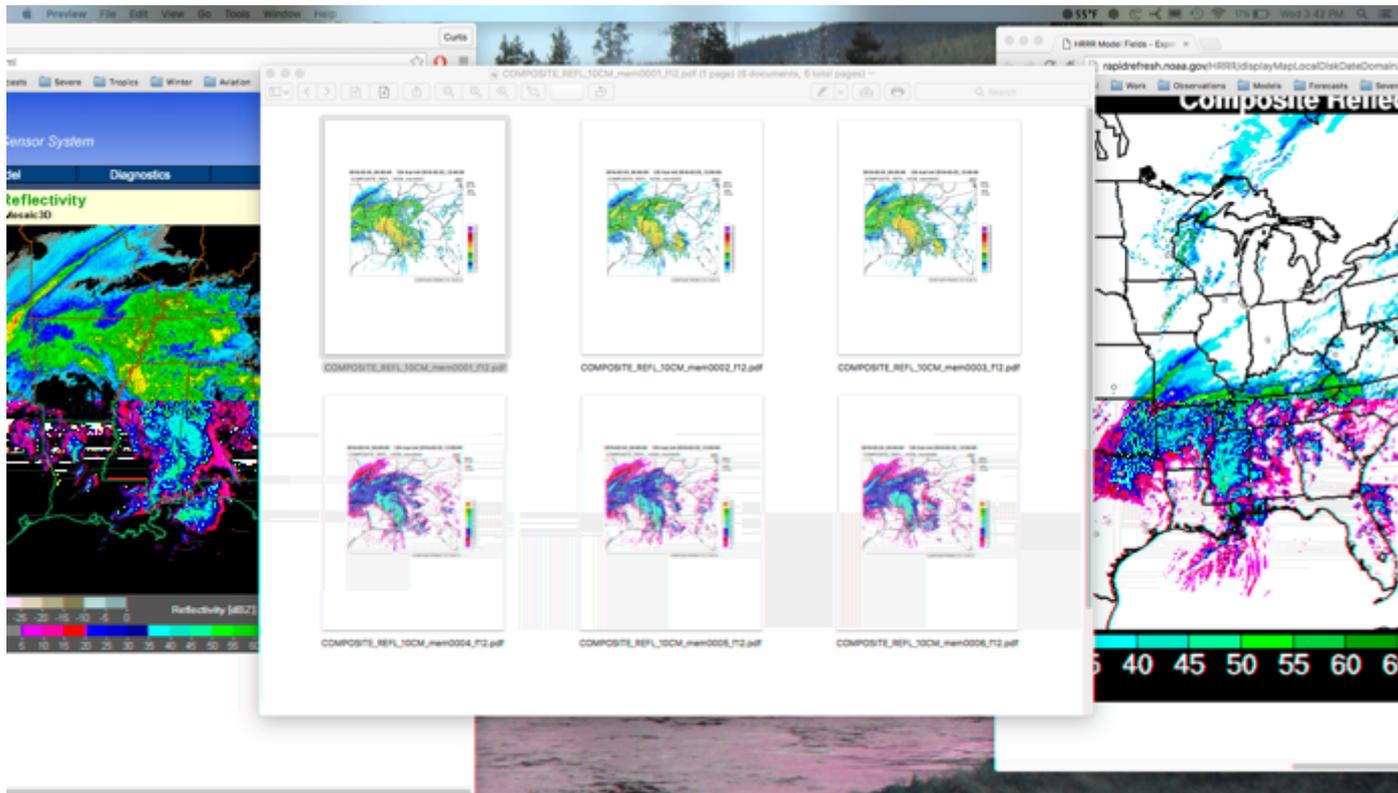
# HRRR-TLE: Leading to HRRRE (HREF)

12 hr Forecasts Valid 00 UTC 24 Feb 2016

Observations

Six Member Ensemble

Deterministic HRRR





S

2014: E

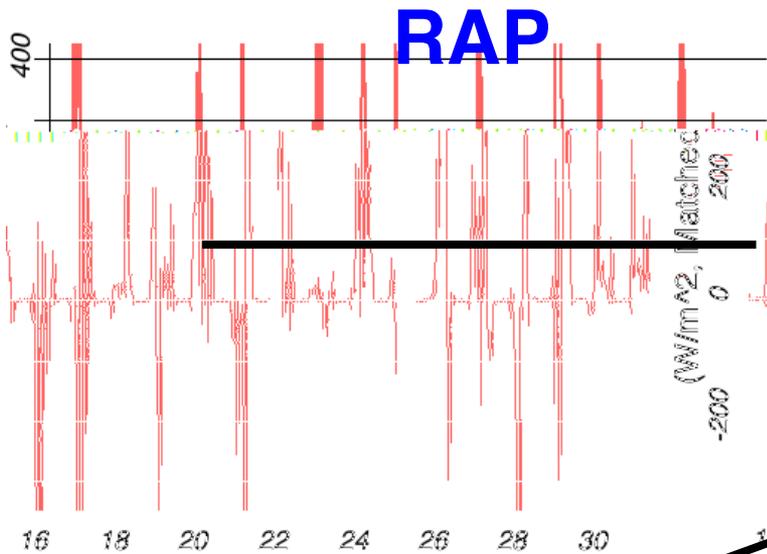
S

I

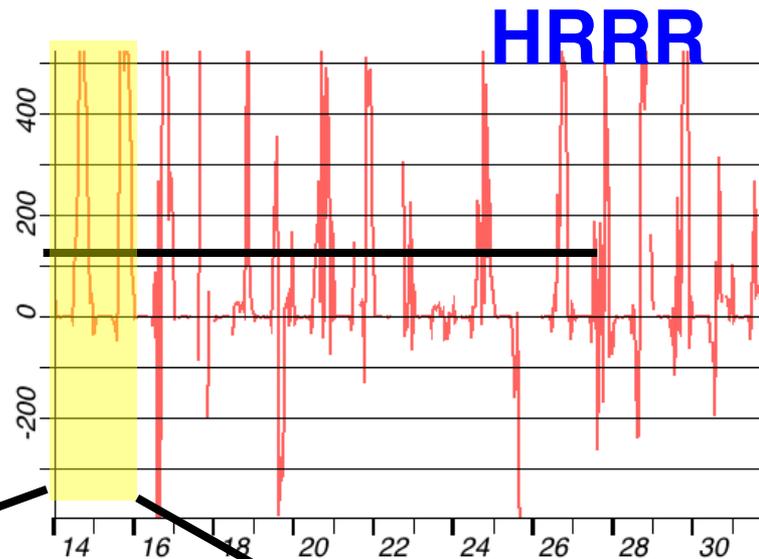
RAP

HRRR

12- GHI F B B , I (W -2)



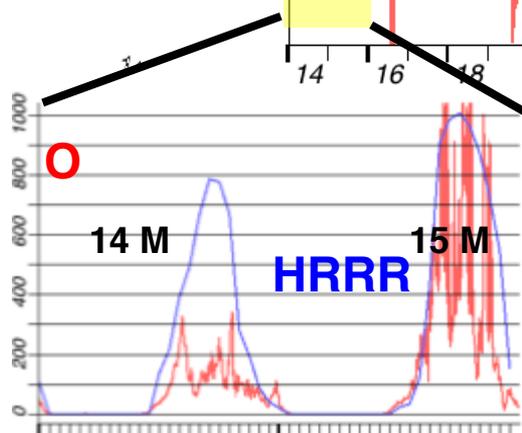
RAP



HRRR

M  
2014

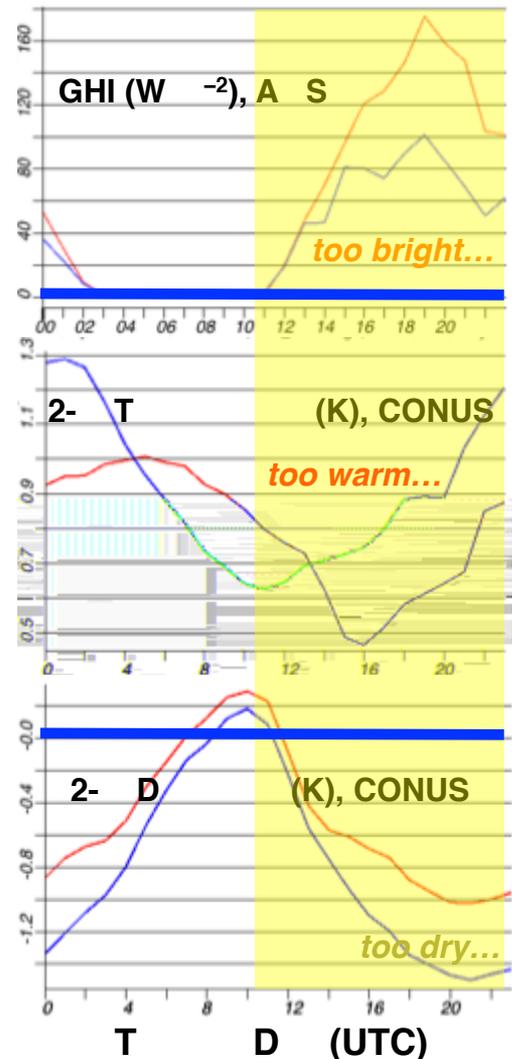
M  
2014



14 M

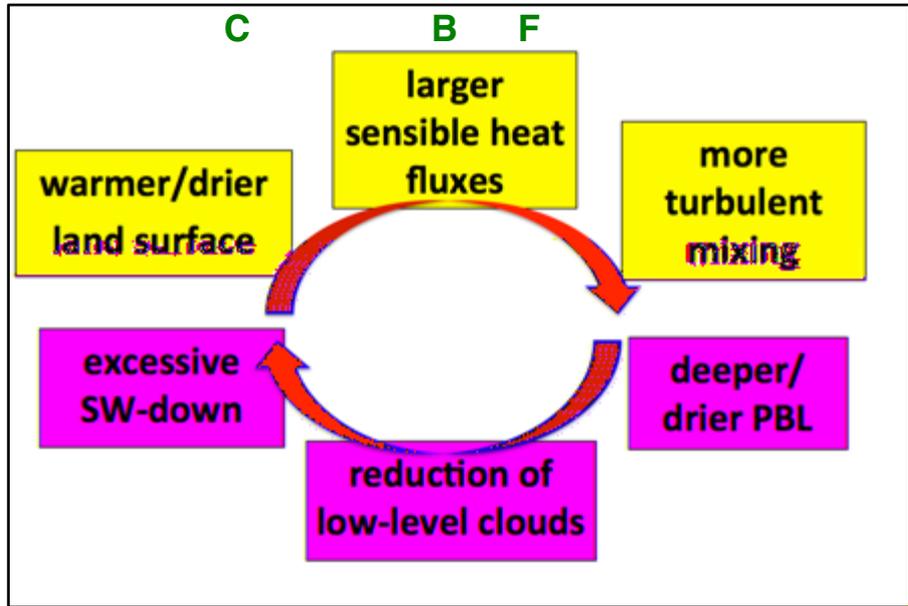
HRRR

15 M



12- F B  
 14-31 M 2014  
 HRRR  
 RAP

Energy balance at earth's surface. With incorrect components, model will seek its own equilibrium.

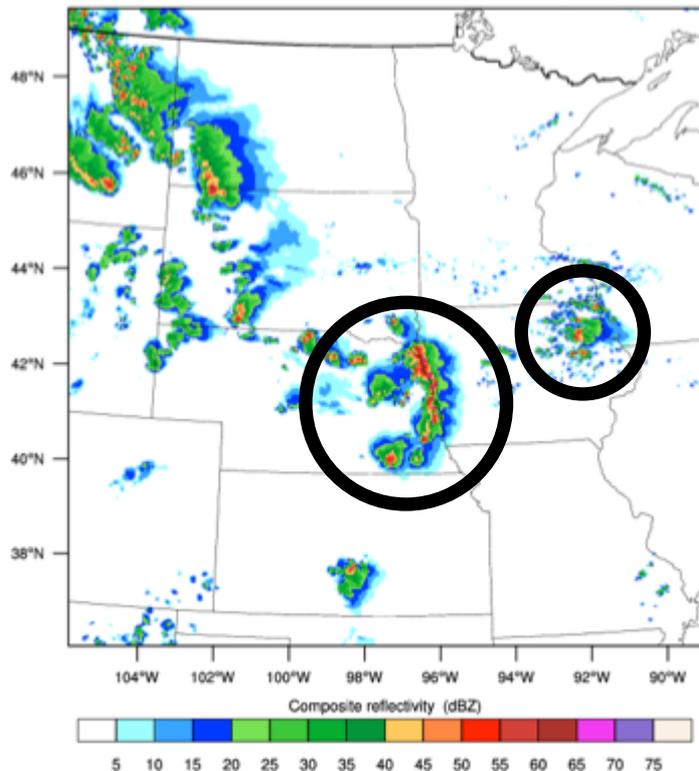




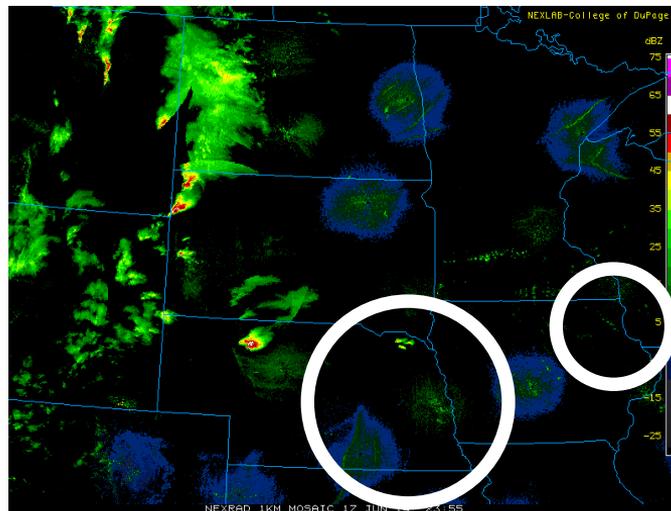
4-

( 0000 UTC 18 J 2014)

Composite reflectivity (dBZ)



O



Source: UCAR

Warm-dry bias  
 Errors in thunderstorm forecasting  
 Errors in solar forecasting, high SW bias overall



# ESRL RAP

# HRRR C

- K

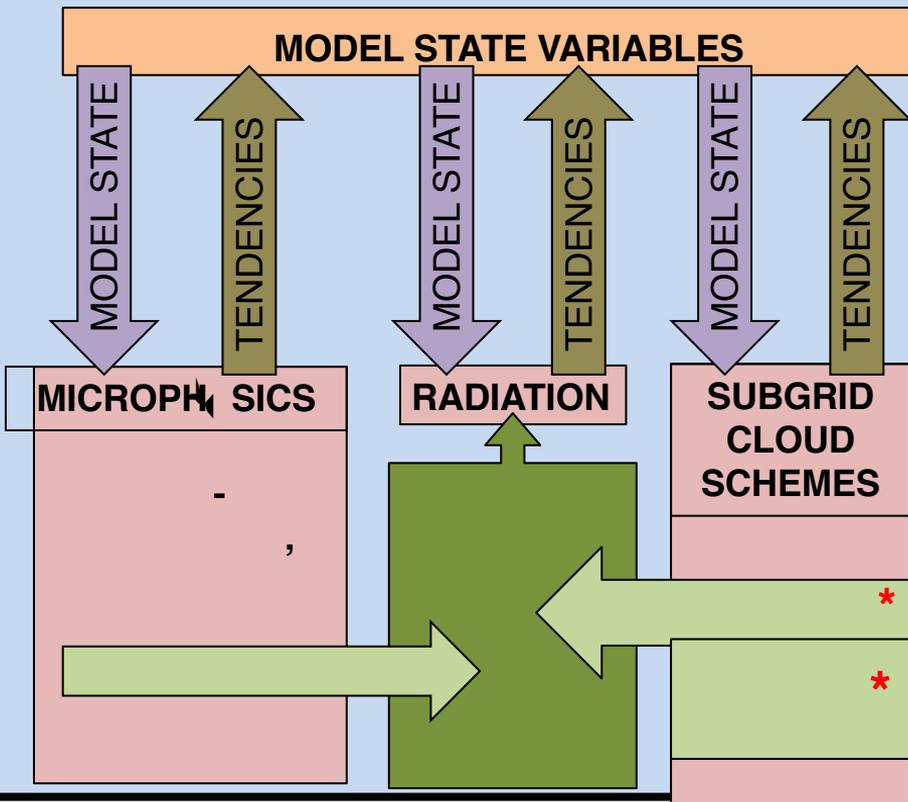
| Model | Domain        | Grid Points | Grid Spacing | Vertical Levels | Pressure Top | Boundary Conditions | Initialized               |
|-------|---------------|-------------|--------------|-----------------|--------------|---------------------|---------------------------|
| RAP   | North America | 758 x 567   | 13 km        | 50              | 10 hPa       | GFS                 | Hourly (cycled)           |
| HRRR  | CONUS         | 1799 x 1059 | 3 km         | 50              | 20 hPa       | RAP                 | Hourly - RAP (no cycling) |

| Model | Version         | Assimilation               | Radar DA       | Radiation LW/SW | Microphysics                       | Convection Deep/Shallow | PBL  | LSM        |
|-------|-----------------|----------------------------|----------------|-----------------|------------------------------------|-------------------------|------|------------|
| RAP   | WRF-ARW v3.6.1+ | GSI Hybrid 3D-VAR/Ensemble | 13-km DF       | RRTMG/RRTMG     | Thompson-Eidhammer (aerosol-aware) | Grell-Freitas-Olson     | MYNN | RUC 9-leve |
| HRRR  | WRF-ARW v3.6.1+ | GSI Hybrid 3D-VAR/Ensemble | 3-km 15-min LH | RRTMG/RRTMG     | Thompson-Eidhammer                 | None / GFO              | MYNN | RUC 9-leve |

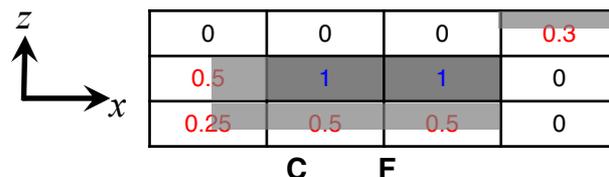
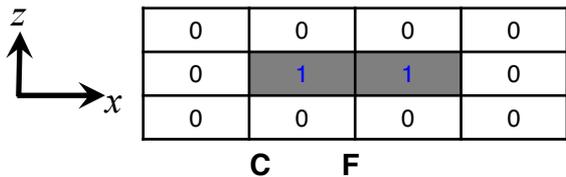
| Model | Horiz/Vert Advection             | Scalar Advection  | Upper-Level Damping | 6 <sup>th</sup> Order Diffusion | Radiation Update | Land Use         | MP Tend Limit | Time-Step |
|-------|----------------------------------|-------------------|---------------------|---------------------------------|------------------|------------------|---------------|-----------|
| RAP   | 5 <sup>th</sup> /5 <sup>th</sup> | Positive-Definite | w-Rayleigh 0.2      | Yes 0.12                        | 20 min           | MODIS Fractional | 0.01 K/s      | 60 s      |
| HRRR  | 5 <sup>th</sup> /5 <sup>th</sup> | Positive-Definite | w-Rayleigh 0.2      | Yes 0.25 (flat ter              | 15 min           | MODIS Fractional | 0.07 K/s      | 20 s      |



# WRF-ARW

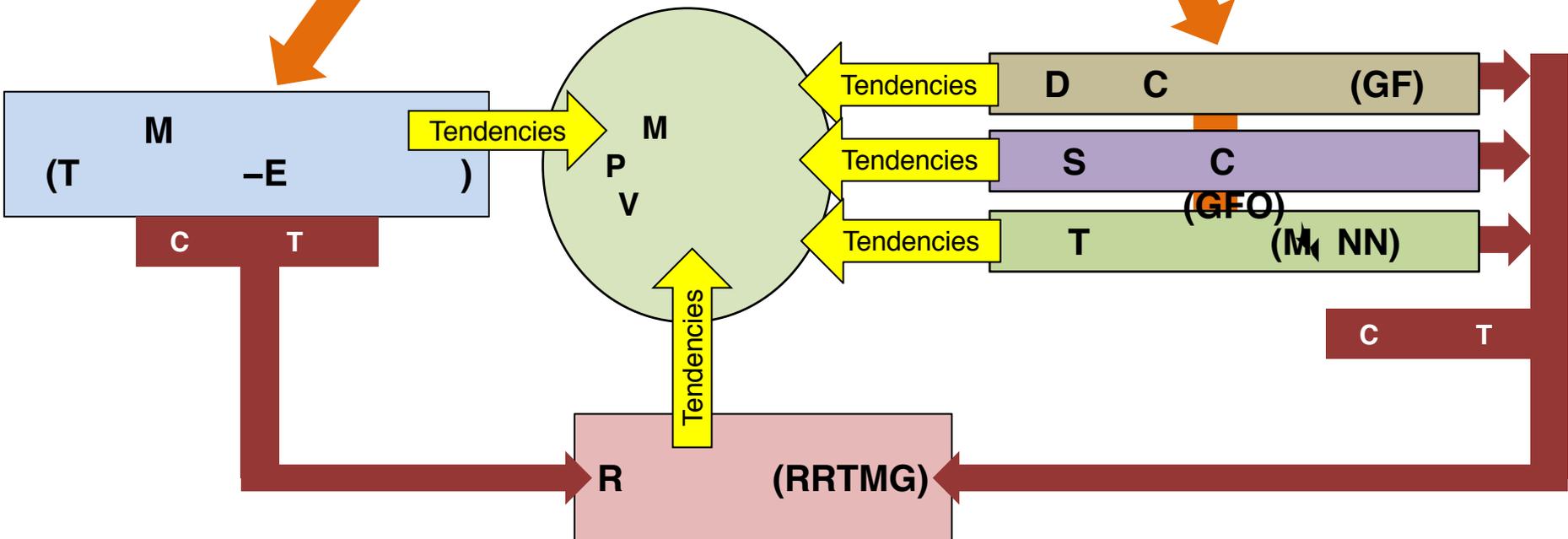


**\*RAP**



**G**    **-S**    **C**  
**R**            **W**    :

**S**            **-S**    **C**  
**R**            **W**    :

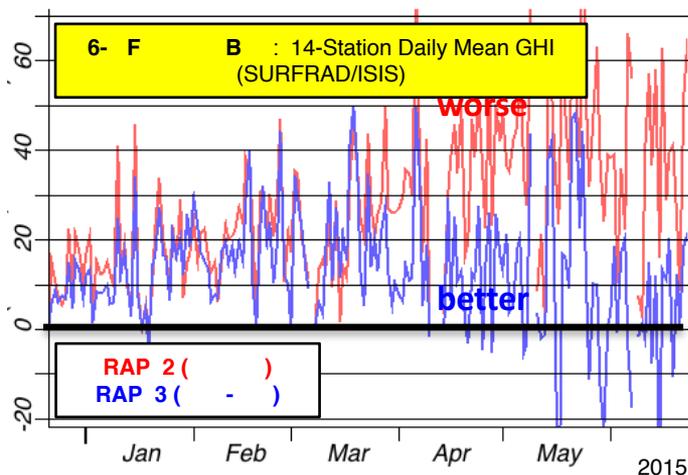


## Solar

- Improved forecasts of GHI by better representation shallow-cumulus (figure on right).
- Further improvements from better representation of stratus is necessary to fix remaining bias (figure on right).
- Aerosol-aware microphysics.
- Improved cloud/hydrometeor assimilation

## Wind

- Promising test results for MYNN-MassFlux.
- More improvements from mixing length revision.
- Future development work: momentum flux in mass-flux scheme.



## Ongoing Collaborations

- Solar Forecast Improvement Project (SFIP; Dept. of Energy) (*project on hiatus with NOAA/ESRL*)
- Wind Forecast Improvement Project II (WFIP2; Dept. of Energy)

<http://rapidrefresh.noaa.gov/HRRRwfipsubh/Welcome.cgi>

<http://www.esrl.noaa.gov/psd/psd3/wfip2/>

- ***Progress toward Improved Solar Forecasts in HRRRv2/RAPv3 (ESRL now, NCEP May 2016)***
  - Energy-related improvements in HRRR/RAP also benefit severe-weather, aviation, hydrology forecasts
  - ***Direct SW, 15-min mean fields added to GHI in RAPv3/HRRRv2 output***
- Improved subgrid-scale cloud scheme in development
  - Provides representation of subgrid stratus, cirrus
  - In ESRL HRRRv3/RAPv4 starting March 2016



$$\begin{aligned}
 u_t - (\zeta + f)v + \frac{\partial(M + E_K)}{\partial x} - \Pi \frac{\partial \theta}{\partial x} + \left( \dot{s} \frac{\partial p}{\partial s} \right) \frac{\partial u}{\partial p} &= F_u \\
 v_t + (\zeta + f)u + \frac{\partial(M + E_K)}{\partial y} - \Pi \frac{\partial \theta}{\partial y} + \left( \dot{s} \frac{\partial p}{\partial s} \right) \frac{\partial v}{\partial p} &= F_v
 \end{aligned}$$

**Force = mass \* acceleration**

$$\left( \frac{\partial p}{\partial s} \right)_t + \nabla_s \cdot \left( \vec{V}_h \frac{\partial p}{\partial s} \right) + \frac{\partial}{\partial s} \left( \dot{s} \frac{\partial p}{\partial s} \right) = 0$$

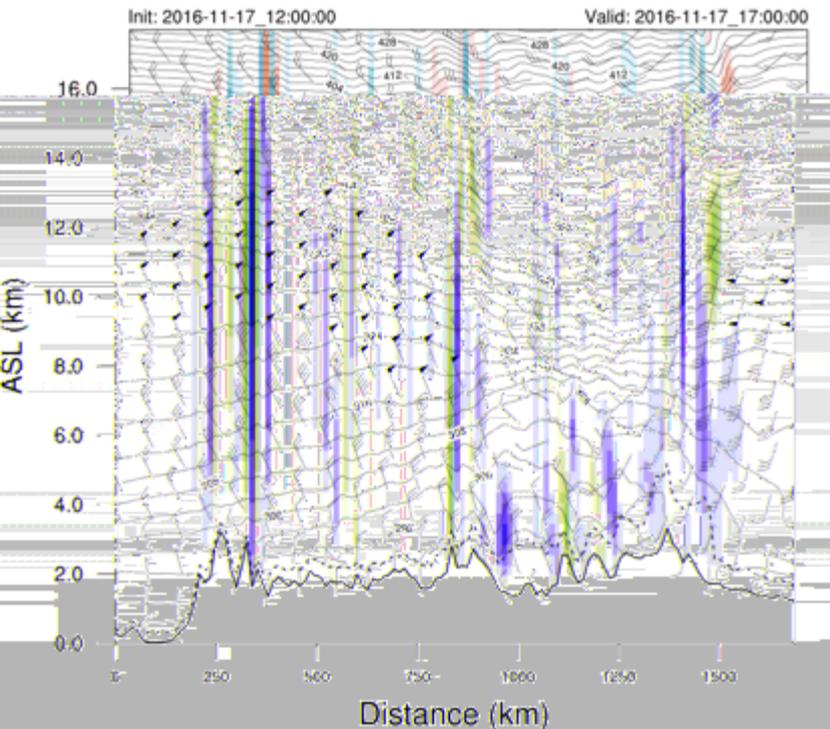
$$\left( \theta \frac{\partial p}{\partial s} \right)_t + \nabla_s \cdot \left[ \left( \vec{V}_h \frac{\partial p}{\partial s} \right) \theta \right] + \frac{\partial}{\partial s} \left[ \left( \dot{s} \frac{\partial p}{\partial s} \right) \theta \right] = F_\theta$$

$$\left( q \frac{\partial p}{\partial s} \right)_t + \nabla_s \cdot \left[ \left( \vec{V}_h \frac{\partial p}{\partial s} \right) q \right] + \frac{\partial}{\partial s} \left[ \left( \dot{s} \frac{\partial p}{\partial s} \right) q \right] = F_q$$

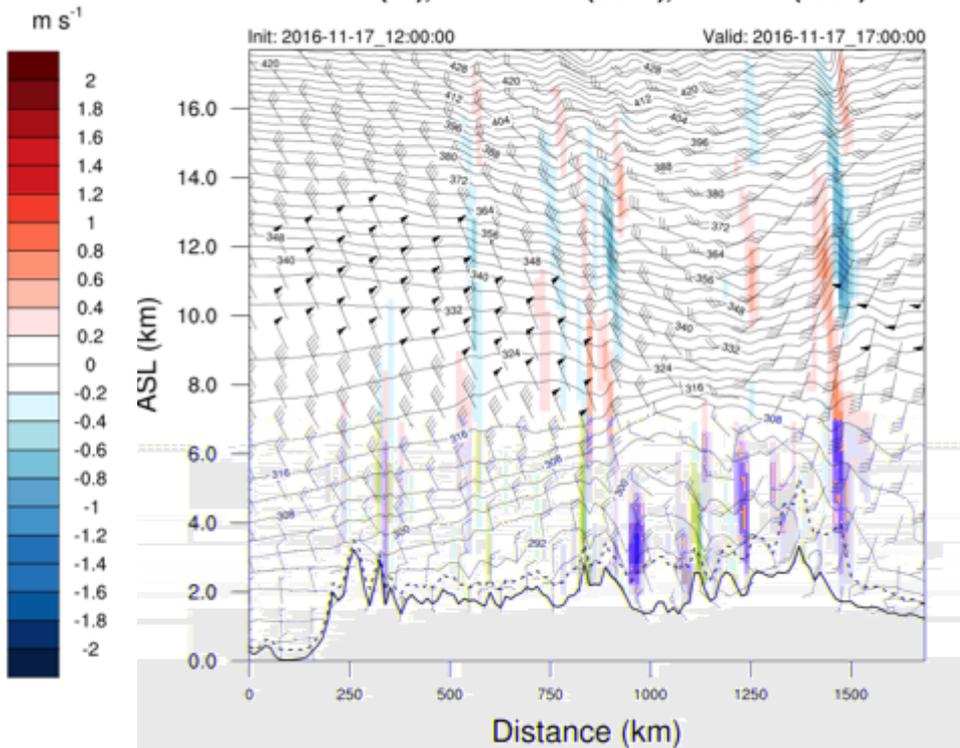
$$\frac{\partial M}{\partial \theta} = \Pi; \Pi = C_p \left( \frac{p}{p_0} \right)^{R/C_p} ; M = C_p T + \phi$$



VVEL (fill), POTL TEMP (black), PBL TOP (dash)



VVEL (fill), POTL TEMP (black), PBL TOP (dash)





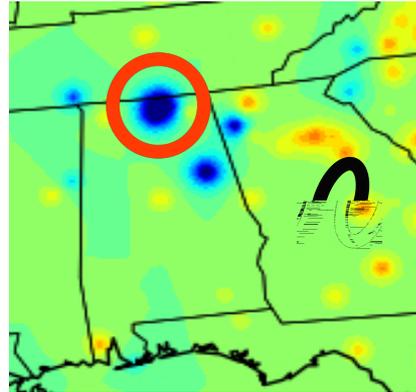
**CLEARING**  
**Negative increment**



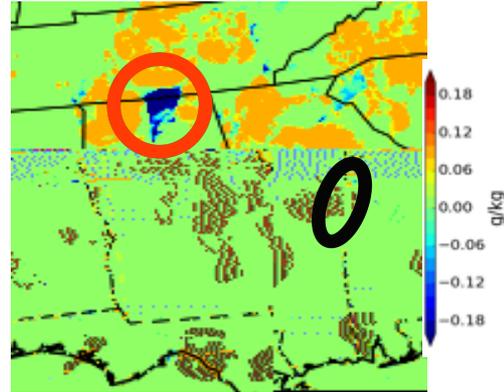
**Observed cloud**  
**Background cloud**  
**→ No increment**



**Var increments**



**Non-var increments**



**Terra  
 Ladwig  
 Talk -  
 Mon**

